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DEVELOPMENT OF NAVAL DIESEL ENGINE DUTY CYCLES FOR AIR
EXHAUST EMISSION ENVIRONMENTAL IMPACT ANALYSIS

by

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B.S., Environmental and Resource Engineering
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Science and Forestry (1983)

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Partial Fulfillment of the Requirements for the Degrees of

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and

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ABSTRACT

A strategy for testing naval diesel engines for exhaust emissions was developed. A survey of existing international and national standard diesel engine duty cycles was conducted. All were found to be inadequate for testing and certification of engine exhaust emissions from naval diesel powered ships. Naval ship data covering 11,500 hours of engine operation of four U.S. Navy LSD 41 Class amphibious ships was analyzed to develop a 27 point class operating profile. A procedure combining ship hull form characteristics, ship propulsion plant parameters, and ship operating profile was detailed to derive an 11-Mode duty cycle representative for testing LSD 41 Class propulsion diesel engines. A similar procedure was followed for ship service diesel engines. Comparisons with industry accepted duty cycles were conducted using exhaust emission contour plots for the Colt-Pielstick PC-4B diesel engines. Results showed the 11-Mode LSD 41 Class Duty Cycle best predicted ship propulsion engine emissions compared to the 27 point operating profile propeller curve. The procedure was applied to T-AO 187 Class with similar results. The application of civilian industry standards to measure naval diesel ship propulsion engine exhaust emissions was found to be inadequate. Engine exhaust flow chemistry post turbocharger was investigated using the SANDIA Lab computer tool *CHEMKIN*. Results showed oxidation and reduction reactions within exhaust gases are quenched in the exhaust stack. Since the exhaust stream in the stack is unreactive, emission sampling may be performed where most convenient. A proposed emission measurement scheme for LSD 41 Class ships was presented.

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CHAPTER 1: INTRODUCTION

1.1 Naval Diesel Engine Background

Heat engines have been in practical use as prime movers for ship propulsion for the last 210 years. During the late eighteenth century the first steam powered ships were built. Although several operative steam powered ships were built during that time period, the *PYROSCAPHE*, built by Claude de Jouffroy d'Abbans in 1783 at Lyons, France, is generally accepted as the first successful application of steam-powered propulsion to ships.¹ These early steam plants burned a coal-gas air mixture at atmospheric pressure. Over the next 100 years the efficiency of the steam engine increased; gradually steam replaced wind power for ship propulsion.

By the late 1800's liquid fuels had gained in popularity. The efficiency of existing heat engine designs which used liquid fuels was limited. Spark ignition gasoline fueled engines were the predominate internal combustion engine in use up to this time. Auto-ignition combustion (knock) of the fuel limited the compression ratios of these engines and, therefore, their efficiency. In these engines, fuel was mixed with the intake air before entry into the engine cylinder. As the mixture was compressed in the cylinder auto-ignition of the fuel, prior to spark discharge, occurred in engines with higher compression ratios.

In 1892 Rudolf Diesel, a German engineer, patented a new type of high pressure reciprocating heat engine. In 1905 J.R. Buchi, a Swiss engineer, laid

¹Thomas C. Gillmer, Modern Ship Design, p. 115.

the foundation for modern exhaust gas turbocharging. In 1910 James McKechnie, an English engineer, obtained a British patent for high pressure fuel injection. These three technologies combined to make the diesel engine of today. In this engine auto-ignition became a benefit. Fuel was introduced after the in-cylinder compression of the air charge. The heat generated by the gas compression initiated combustion after fuel injection. With this engine design, higher compression ratios were possible. The amount of work available per unit of fuel burned increased, raising efficiency. The diesel engine designs of today retain efficiency advantages over both spark ignition and gas turbine internal combustion engines.

In the summer of 1913 two civilians from the New York Navy Yard, Albert Kloppenberg, a draftsman, and Ernest Delbose, an engineer, together with a US Naval Officer, Lieutenant Chester W. Nimitz, were sent to Germany. They went to observe German large diesel design, construction and ship installation techniques. Prior to this time, the U.S. Navy had only limited experience with small diesel engines used in submarines. As a result of their study, the first U.S. Navy surface ship to be powered by diesel engines, the *USS MAUMEE*, was commissioned on October 23, 1916. The hull of the ship, a new 14,500 ton oiler, had been built on the west coast of the United States and towed to the New York Navy Yard in Brooklyn, New York. There, twin 2,600-horsepower diesel engines were built and installed under the supervision of Lieutenant Nimitz. The engine

design of *MAUMEE* borrowed heavily from German technology.²

In the past thirty years diesel engines have replaced steam plants as the propulsion plant of choice for many commercial ships. Most U.S. Navy ships are equipped with diesel generators for emergency electrical power. Some use diesel generators for ships service electric load; a smaller number (69) have diesel main propulsion.³

Diesel engines procured for the navy must successfully pass the 1,000 hour durability test outlined in Military Specification MIL-E-21260D *Engines, Diesel Marine, Propulsion and Auxiliary, Medium Speed*, of March 1976. No procedure is currently specified by the Navy to test diesel engines for exhaust emissions during the procurement process, or when operational with the fleet. The goal of this thesis is to develop naval diesel engine exhaust air emission test procedures.

The cargo variant of the LSD 41 Class of ships is still under construction for the U.S. Navy. This ship class is the most modern diesel ship in the U.S. Navy fleet. It features an automated engine bell recording system, automated diesel trend analysis collection, and has achieved a very high engine reliability rating. For these reasons it was selected for study in this thesis.

²E.B. Potter, *NIMITZ*, p. 125.

³Naval Sea Systems Command, "Internal Combustion Engine Exhaust Emission Study," 1991, p. 7-18.

1.2 LSD 41 Class

The twelve ships of the LSD 41, *WHIDBEY ISLAND*, Class have four medium speed Colt SEMT-Pielstick 16 PC2.5 V400 diesels, each rated at 8,500 brake horsepower for main propulsion. Two diesels are connected by clutch to a mechanical reduction gear which drives the 13.5 foot diameter controllable reversible pitch propellers through a propulsion shaft. The combined 34,000 brake horsepower (33,000 shaft horsepower) propels the two shafts and powers the 15,745 ton ship to a maximum speed of approximately 22 knots. Ships service electrical power is provided by four Fairbanks Morse 38ND8-1/8 opposed piston diesel engine driven 1300 kW electrical generators.

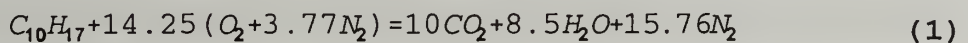
The LSD 41 Class is comprised of eight ships of landing-ship-dock configuration and four cargo carrying variants. The mission of this ship class is to provide amphibious assault capability to 450 troops and four air cushion landing craft. This ship is designed and built to operate within visual range of shore and has been recently deployed in support of United Nations initiatives in Iraq, Somalia, and Haiti.

1.3 Pollutants of Interest

Since the beginning of human of civilization the benefit of increased industrialization has brought with it the price of pollution. In our modern world the internal combustion engine is the workhorse of commerce. As a source of power, its high energy conversion to weight density has made it the engine of choice for powering our automobiles, trucks, aircraft, and ships. With the shift

from wind powered sailing ships, and horse drawn vehicles has come an increase in anthropogenic atmospheric chemicals. These pollutants have degraded the quality of life of our civilization by endangering public health, degrading the public welfare in decreased visibility and by damaging our buildings and natural world.

Like all internal combustion engines, diesel engines intake fresh air, burn a fuel/air mixture, produce work and exhaust gases. Currently, the diesel cycle is the most efficient of the heat engine cycles widely used. However, processes such as incomplete fuel combustion, engine friction, and heat losses all reduce efficiency. The complete stoichiometric combustion of diesel fuel is given by equation (1):



Complete stoichiometric combustion is rarely achieved because of nonuniform mixing of air and fuel. Diesel engines are operated with excess air (lean) to enhance the combustion process. Within the cylinder of a typical diesel engine, combustion takes place under different regimes. In those areas where stoichiometric conditions exist, complete combustion occurs. These areas are typified by high temperature leading to oxidation of atmospheric nitrogen and production of nitric oxide (NO) and nitrogen dioxide (NO₂). Oxides of nitrogen (NO_x) are comprised of NO (80-90%) and NO₂ (10-20%).

Surrounding the stoichiometric regions are fuel lean and fuel rich areas.

The fuel lean regions are typified by lower temperatures and complete fuel combustion due to an excess of oxygen and the dilutive effect of excess air. The fuel rich regions have incomplete combustion due to a shortage of oxygen. In these areas carbon monoxide (CO) and pyrolyzed and unpyrolyzed fuel hydrocarbons (HC) are produced. Since diesel engines are normally operated fuel lean CO and HC products are not a substantial problem. Carbon dioxide (CO₂) and water (H₂O) are the ultimate products of complete fossil fuel combustion. The rate of CO₂ production increases with combustion efficiency. Optimization of the combustion process leads to an increase in CO₂ production, a gas generally accepted as contributing to global warming by the green house effect.

Normal engine operation encompasses both steady state and transient conditions. Transient conditions occur during acceleration and deceleration between steady state conditions. During transients the fuel-to-air ratio changes, engine responsiveness is limited by the air intake system. The result is fuel rich combustion. Transient conditions are characterized by decreased NO_x and increased CO, HC and PM levels in the exhaust.

Diesel fuel contains a small (1-5%) amount of sulfur which combines with oxygen in the combustion chamber to form sulfur oxides (SO_x). Sulfur oxides have been shown to contribute to acid rain, degrade visibility and increase human respiratory problems. The problem of sulfur is being addressed by the specification for low sulfur fuels.

The State of California has completed several air quality studies. These indicate marine vessels substantially contribute to pollutants in the ambient air inventory. Table 1-1 provides a comparison of marine vessel emissions versus other sources for the state of California in 1987. Contained in the study are emissions from all vessels, including diesel, gas turbine, and steam powered vessels. The vast majority of the approximately 22,500 vessels which operated in California waters during 1987 were diesel powered. Economic pressures forced the conversion of most steam and gas turbine commercial ships to more efficient diesel power during the 1970's and 80's. However, this trend has had a negative impact on ambient air quality as diesel engines produce about 10 times more NO_x than steam boilers.⁴ The percent contribution of NO_x and SO_x by marine vessels is primarily due to lack of emission regulation compared to other

Table 1-1: Marine Vessels Versus Other Sources (tons/day)⁵

Source	HC	CO	NO _x	SO _x	PM
Stationary	5,300	6,000	970	210	11,000
On-Road	1,600	11,000	1,900	130	270
Off-Road	341	4,005	789	50	58
Marine Vessels	29	57	412	226	28
Total	7,270	21,062	4,071	616	11,356
% Marine	0.40	0.27	10.1	36.7	0.25

⁴State of California Air Resources Board, "Public Meeting to Consider a Plan for the Control of Emissions from Marine Vessels," p. 2, 1991.

⁵Ibid., p. 9.

more numerous sources, and the high sulfur content of fuels used for commercial diesel powered ships. Marine vessel emissions are further broken down by vessel type (Table 1-2) and location (Table 1-3).

Table 1-2: Marine Vessel Emissions by Vessel Type (% Contribution)⁶

Vessel Type	Number	NO _x	SO _x
Ocean-Going	15,491	74 %	69 %
Harbor	268	2 %	15 %
Commercial Fishing	6,807	24 %	16 %

Table 1-3: Marine Vessel Emissions by Vessel Location (tons /day)⁷

Vessel Location	NO _x	SO _x
In-port	74 (18%)	34 (15%)
At-sea	238 (58%)	155 (69%)
Commercial Fishing	100 (24%)	37 (16%)
Total	412 (100%)	226 (100%)

Marine diesel pollutants of prime importance for future regulation are NO_x and particulate soot (PM) which is comprised of carbon and imbedded hydrocarbons. A relationship has been determined to exist between NO_x and PM. Engine in cylinder design changes to reduce NO_x generally correspond to an increase in PM production. Therefore, diesel engine designers trade off fuel efficiency and reduced NO_x against increased PM. Figure 1 demonstrates that

⁶Ibid., p. A-3.

⁷Ibid., p. A-2.

the rate of PM emissions trade-off tends to increase exponentially as the NO_x emission level gets lower.⁸ The curve of Figure 1 represents the technology average for on-highway heavy-duty engines produced between 1988 and 1990.

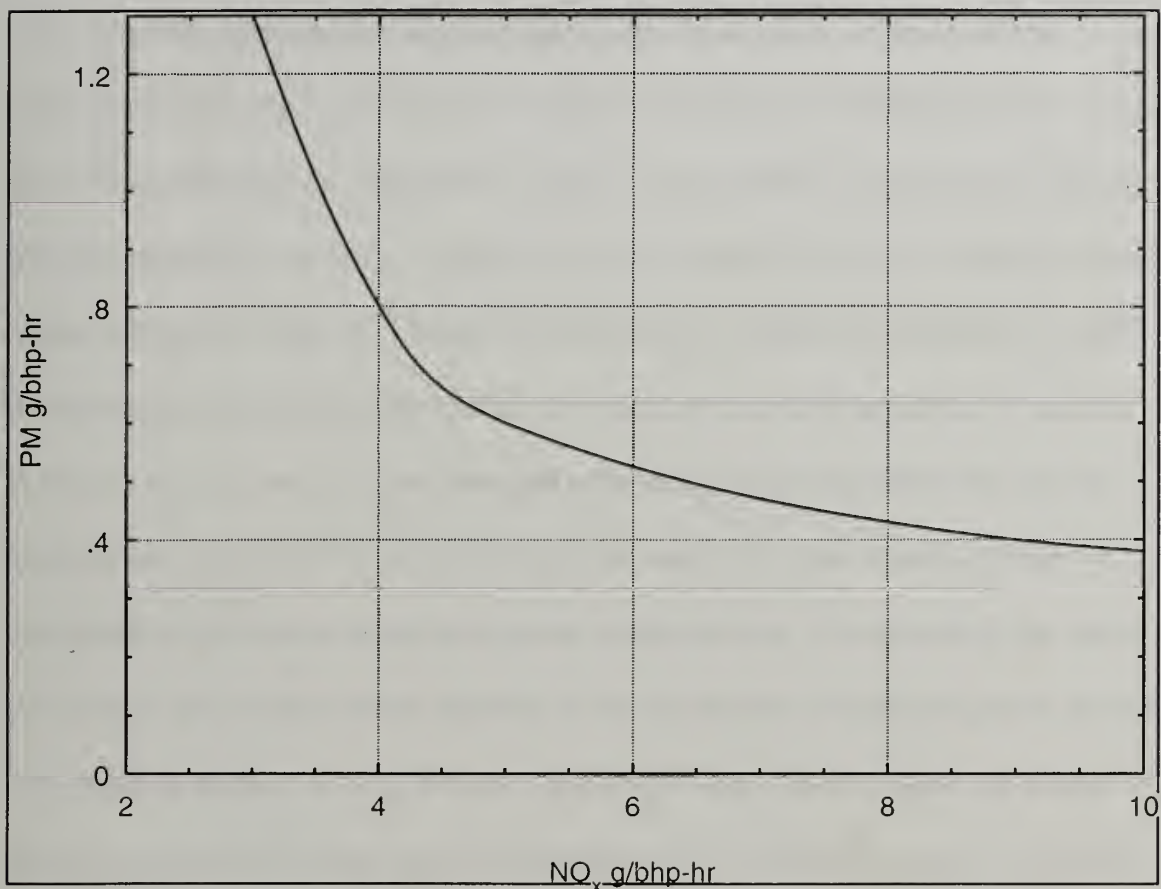


Figure 1: Particulate - NO_x Trade Off

Engine exhaust emissions from ships present a more complex analytic problem than non marine sources. Unlike trucks and locomotives, marine diesel engines are connected to a long exhaust pipe (uptake). The LSD 41 Class has two exhaust stacks, each of which contain the uptakes of two main propulsion

⁸"Control of Air Pollution: Emissions of Oxides of Nitrogen and Smoke From New Nonroad Compression-Ignition Engines at Above 50 Horsepower," Federal Register, Volume 58, No. 93, 17 May 1993, p. 28836.

and two ship service diesel engines. Within the uptake, gases may continue to react with each other and ambient air, oxidation and reduction processes continue driven by temperature. Therefore, emissions from the engine exhaust valve may be different than what ultimately exits the stack. After treatment schemes such as selective catalytic reduction (SCR) take advantage of exhaust gas stream chemistry to reduce NO_x levels. Since ambient air quality is directly affected by stack emissions, regulatory action should be stack (or uptake) based rather than engine based. However, the diversity of diesel engines and uptake designs would complicate traditional command and control regulation if applied to ships. For this reason, the chemical processes occurring within the uptake must be well understood to equate engine to stack (or uptake) emissions over the spectrum of engine speed and power combinations. Complicating the stack (or uptake) gas measurement scheme is the distribution of exhaust gases across the uptake diameter. The turbulent nature of the gas stream makes prediction of gas levels at distinct locations very difficult due to associated velocity, pressure, and temperature gradients. Continued degradation of urban ambient air quality has resulted in increasingly tougher legislative and regulative initiatives to reduce the emission of diesel generated NO_x , CO , SO_x and PM. Current understanding of uptake gas chemistry does not allow accurate emission prediction at the stack exit. As regulations drive emissions downward, reliance on diesel engine derived emission criteria for procurement and trend analysis coupled with the beneficial effects of mixing and cooling in the uptake, and stack

exit monitoring for certification and compliance will give the U.S. Navy the best means for conforming to emission standards.

1.4 Legislative Initiatives

The International Maritime Organization (IMO) has acknowledged that national and regional legislation to limit engine exhaust emissions from ships is inevitable. In response, the IMO's Marine Environmental Protection Committee (MEPC) is currently working on standards for the prevention of air pollutants from ships. Specifically targeted is the reduction of NO_x and SO_x without an increase in other air pollutants. IMO has agreed to formulate a new annex to the International Convention for the Prevention of Pollution from Ships (MARPOL) 73/78. The new annex, Annex 6, will apply to new diesel engines over 100 kilowatts, and to non-public vessels over 500 gross tons. Proposed SO_x reduction of 50 percent of 1992 levels by 2000 is to be accomplished by a global cap of 3-4 percent fuel sulfur content and a limit of fuel sulfur of 1.5 percent on a regional basis in special areas. For new engines, 70 percent reduction of 1992 levels by 2000 for NO_x have been proposed. IMO anticipates completing work on Annex 6 by the end of 1994. Although the U.S. Coast Guard has participated in the development of Annex 6 as the official representative of the U.S. government, ratification by the U.S. Congress would be required to make Annex 6 law. Even though Annex 6 will likely exempt public vessels, it is probable that the U.S. Congress will mandate public vessel compliance upon ratification. Congress did just that when it ratified Annex 5 to MARPOL 73/78 in 1987

requiring public vessels to comply with the commercial standards. Regardless of what occurs in the international arena, control of emissions has been a priority of all levels of government within the United States.

The U.S. Congress enacted the Clean Air Act (CAA) in 1970. The central theme of the CAA is a cooperative federal-state scheme to achieve nationwide acceptable air quality. Section 108 and 109 of CAA require the Administrator of the Environmental Protection Agency (EPA) to establish national ambient air quality standards (NAAQS) for criteria pollutants. The six primary and secondary NAAQS that have been designated by the Administrator appear in Table 1-4. Primary standards are set to protect the public health with an adequate margin of safety. Secondary standards have been established to protect the public welfare from any known or anticipated adverse effect associated with the presence of such air pollutant in the ambient air.

Section 110 of CAA requires each state to develop State Implementation Plans (SIP's) to achieve the federally mandated primary and secondary NAAQS. In SIP development a state must include enforceable emission limitations and other control measures. The amendments of 1990 added the requirement for states with areas not in attainment to establish vehicle monitoring programs to ensure continued compliance with tailpipe standards.

The CAA in section 202 established emission standards for new motor vehicles or new motor vehicle engines. Specific on-road standards for light duty vehicles and light duty trucks for CO, HC and NO_x were specified in the act.

Table 1-4: National Ambient Air Quality Standards

Criteria Pollutant	Primary Standard	Secondary Standard
Carbon Monoxide (CO)	35 ppm averaged over 1 hour and 9.0 ppm averaged over 8 hours.	None.
Particulate Matter (PM ₁₀)	150 µg/m ³ averaged over 24 hours, once per year, and 59 µg/m ³ or less annual arithmetic mean.	Same as primary.
Lead (Pb)	1.5 µg/m ³ arithmetic average over a calendar quarter.	Same as Primary.
Nitrogen Dioxide (NO ₂)	100 µg/m ³ as annual arithmetic mean.	Same as Primary.
Ozone (O ₃)	235 µg/m ³ averaged over 1 hour, one exceedance per year.	Same as Primary
Sulfur Oxides (SO _x)	365 µg/m ³ average over 24 hour period, one exceedance per year; 80 µg/m ³ annual arithmetic mean.	1,300 µg/m ³ average over a 3-hour period, one exceedance per year.

Section 213 of the act tasked the administrator to conduct a study of emissions from nonroad engines and nonroad vehicles to determine if such emissions cause, or significantly contribute to, air pollution which may reasonably be anticipated to endanger public health or welfare. Further, this section required the administrator to issue emission standards for the nonroad source if it is found to endanger public health or welfare. Section 209(e)(2)(A) authorizes the state of California to adopt and enforce standards and other requirements relating to the control of emissions from nonroad engines or

vehicles not covered elsewhere in the act. Marine vessels and engines are subject to regulation under this section.

The State of California Legislature enacted the California Clean Air Act (CCAA) in 1988 to fulfill its unique status under the federal CAA to pioneer air quality improvement initiatives. Under this act, the California Air Resources Board (CARB) was required to consider controlling emissions from several previously unregulated nonroad mobile sources. Marine vessels and engines were included in the act for CARB regulation. CARB has proposed regulation of vessels operating within a zone defined as "California Coastal Waters". This area parallels the California coast and is within 27 miles off Point Conception, and as far as 100 miles off the San Francisco Bay Area. The distances were developed based on meteorological and modeling data showing emissions off the coast affect coastal land areas. Information supplied to CARB by the U.S. Coast Guard indicates all commercial shipping calling at California Ports transits within 20 miles of shore. The U.S. Navy conducts extensive amphibious assault training exercises off the coast of the Camp Pendelton Marine Base in San Diego County, an area within the coastal waters zone. Figure 1 gives a chart of the designated California Coastal Waters. Figure 1 was taken from page 12 of the report commissioned by CARB entitled "Regulatory Strategies for Reducing Emissions from Marine Vessels in California Waters," which was prepared by Sierra Research on 4 October 1991. Also depicted in Figure 1 are the California coastal air management districts (AQMD's).

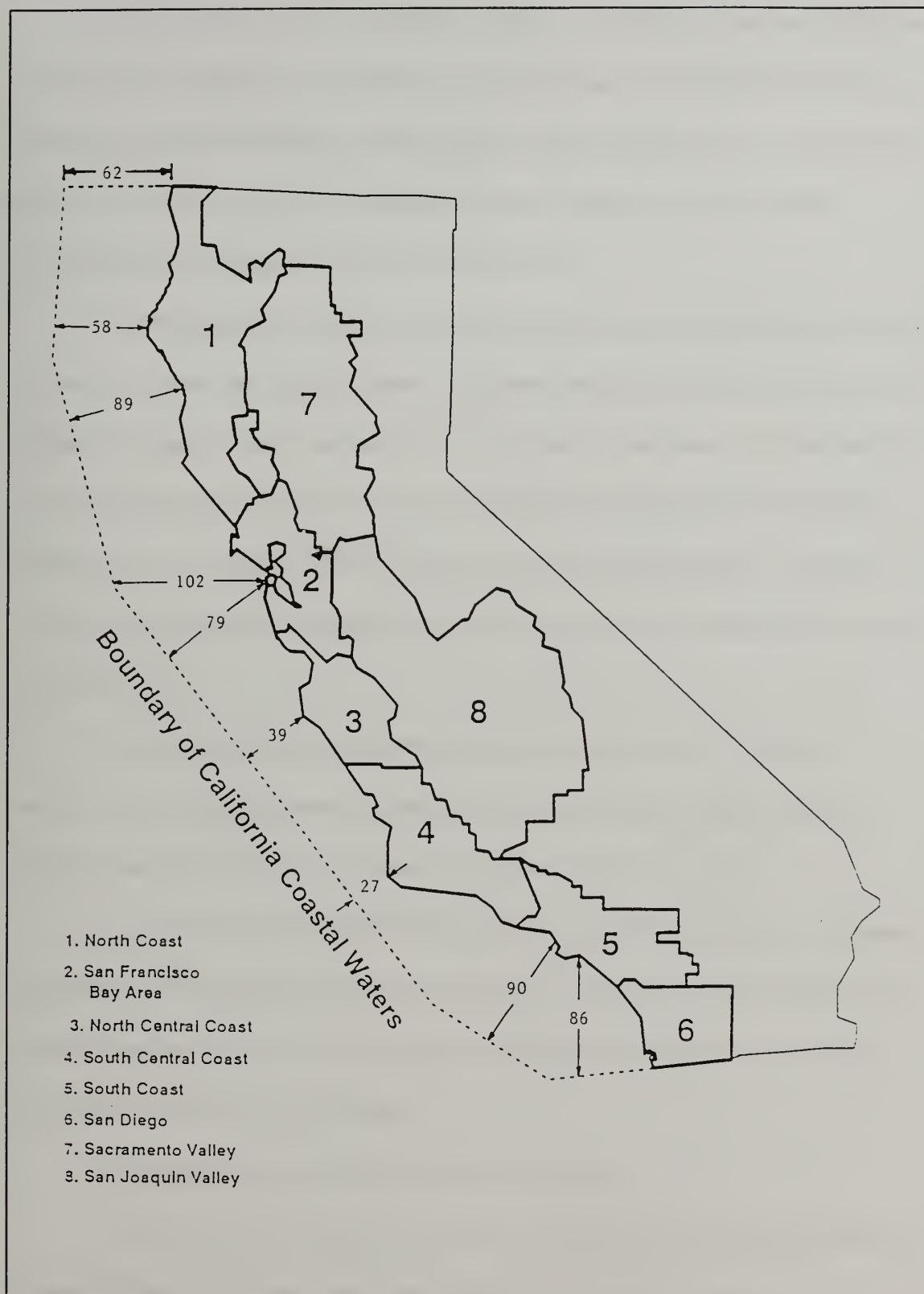


Figure 2: California Coastal Water Air Basins - Distances in Miles

On 24 February 1994, the Administrator of the EPA signed the California Federal Implementation Plan (CFIP). The CFIP was developed by EPA since California had not developed SIP's for each of their AQMD's as it was required to do under CAA. The CFIP maintains the basic elements of the CARB proposed plan and adds an emission fee system.

The fee system proposed in the CFIP significantly impacts frequent users of California ports and high emitters. The basic fee of \$10,000 per U.S. ton NO_x emitted will apply to commercial shipping. Table 1-1 indicates that commercial ships operating in the California Coastal Waters zone emit 412 tons/day NO_x. At this emission rate, \$4,120,000 in fees would be collected daily. Incentives within the fee collection system reward reductions in NO_x. These incentives are as follows:

- 90 percent fee reduction for 80 percent NO_x reduction. Possible methods for accomplishment are through use of selective catalytic reduction (SCR) or shift to gas turbine or diesel propulsion plants.

- 50 percent fee reduction for 30 to 80 percent NO_x reduction. Suggested alternatives for accomplishment are: injection timing retard, engine fine tuning, exhaust gas recirculation (EGR), water emulsification, selective non-catalytic reduction, and reduced ship speed.

- Full fee if less than 30 percent NO_x reduction.

- Fee reduction for use of the relocated Santa Barbara shipping channel (located farther out to sea), and use of shore power when in port.

The fee system is expected to encourage the development of shipboard emission control systems and provide incentives for more efficient operation and use of shore power inport (cold-ironing). Each commercial vessel operating in California coastal waters must report hours of operation and rated power for each engine on board.

Four basic assumptions have been made in developing the fee model:

1. Cruising: 3 - 100 miles from port. Assume 80 percent of rated engine output
2. Maneuvering/Hotelling: <3 miles from port. Assume 25 percent rated output.
3. Auxiliary Engines: Assume 50 percent rated engine output.
4. Baseline emissions from main engines determined from modified engine speed emission model from Japan. This model equates NO_x to RPM and is based upon engine research conducted in Scandinavia and Japan. Figure 3 illustrates this relation.⁹

⁹Larry N. Hottenstein, "International Impact of California's Engine Emissions Regulations," presentation to ASNE Maritime Environmental Symposium '94, 23 February 1994.

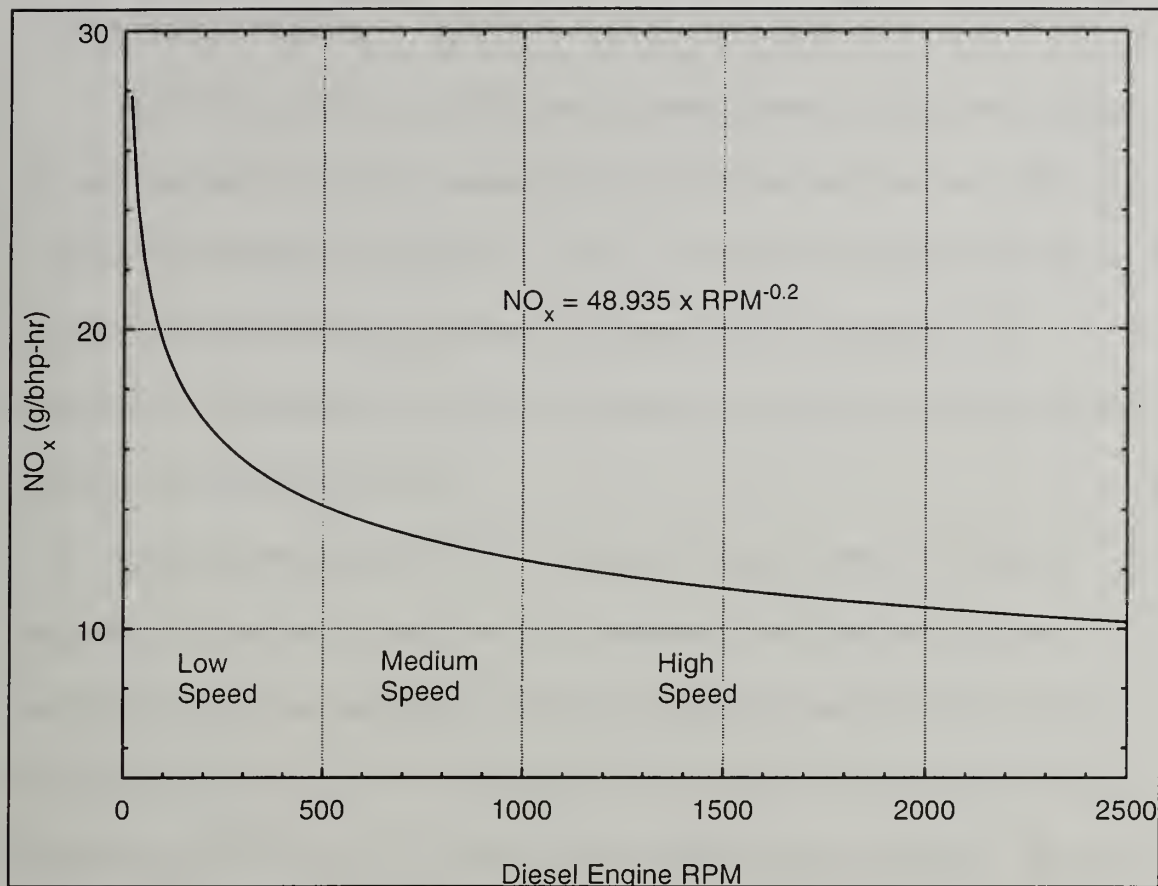


Figure 3: Japanese NO_x Formula

The CFIP presents a clear shift in regulatory strategy. The impact of its full implementation on the work of the IMO and international trade has not been fully assessed. The reliance upon a model equating NO_x to RPM without regard for engine torque or cylinder pressures indicates that the regulatory environment is shifting from analysis to action, but not necessarily the prudent action.

1.5 Regulatory Strategy

The U.S. Congress and EPA have adopted a pareto regulation strategy. To date standards have been established for stationary sources, and light-duty vehicles (automobiles and light-duty trucks). This practice regulates those air pollution sources where the greatest cost/benefit ratio can be had. The emphasis for new regulation in the 1990's will be for the more numerous smaller stationary and mobile sources.

The EPA has broad authority to study, propose, enact, and enforce regulations of mobile nonroad emission sources. The Administrator has periodically published emission controls for heavy duty diesel engines under transient conditions, Table 1-5. Although not binding on marine vessels, these standards offer a preview of probable future marine diesel standards. The trend seen in Figure 4 illustrates the gradual decrease in allowable emissions. EPA has universally defined heavy-duty diesel engines as those installed in a vehicle/vessel of over 33,000 pounds gross vehicle weight.¹⁰ This definition applies to the propulsion and auxiliary engines of large trucks, earth moving equipment, locomotives, and marine vessels. Interestingly, the EPA has adopted a vehicle derived engine classification, instead of one based on horsepower, useful life, etc...

¹⁰PHONECON with Mr. John Roach, EPA Air Quality Division, Boston, MA, of 17 November 1993.

Table 1-5: EPA Heavy-Duty Diesel Emission Standards (g/bhp-hr)

Year	NO _x	PM
1986	10.7	0.60
1990	6.0	0.60
1991	5.0	0.25
1994	5.0	0.10
1998	4.0	0.10
2000*	2.5	0.05

Note: * CARB proposal.

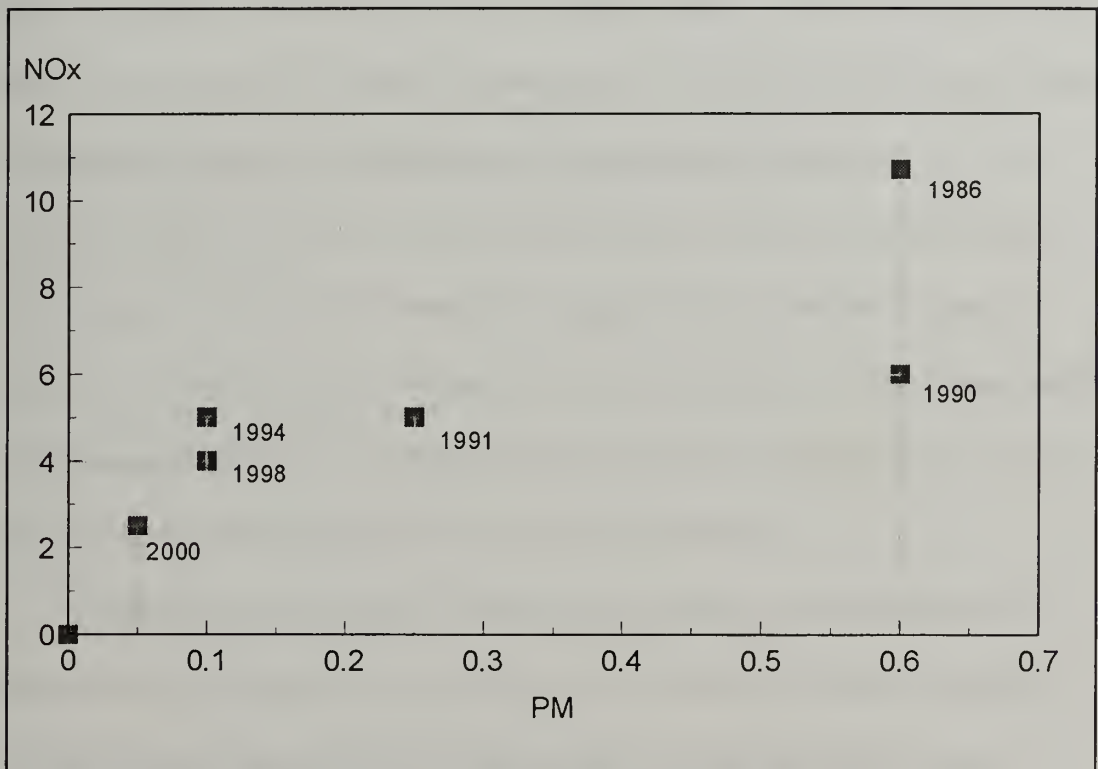


Figure 4: NO_x and PM Heavy Duty Engine Standards

The EPA completed its study of nonroad engine and vehicle emissions in November 1991. Based on this study, on 17 May 1993 EPA proposed nonroad

heavy duty diesel emission standards of 6.9 g/bhp-hr NO_x and proposed smoke opacity standard of 20% during acceleration, 15% on lug mode, and 50% peak opacity on either the acceleration or lug mode. EPA did not issue proposed emission standards for HC, CO and PM. Available test procedures had not been demonstrated capable of predicting these pollutant emissions from nonroad sources. Specifically excluded from these proposed regulations are engines used for main propulsion and auxiliary power in marine vessels. Marine vessel engines were not included for two reasons. First, marine engines are currently subject to safety regulations by the U.S. Coast Guard. EPA must first analyze these current Coast Guard safety requirements, then determine the best method for regulating emissions, consistent with Coast Guard regulations. Second, information was unavailable verifying existing test procedures as applicable to marine engines. EPA must determine a suitable test procedure for marine vessels. Although U.S. Navy vessels are not subject to U.S. Coast Guard safety regulations, the EPA has recognized that existing test procedures may not be adequate for predicting marine diesel engine emissions.¹¹

Regardless of EPA action, CARB has proposed new marine vessel engine emission standards, in-use marine vessel engine emission standards, new and existing source permit requirements, and a broad market based strategy aimed at reducing vessel exhaust emissions effective in 1995. Table 1-6 provides these new proposed NO_x standards applicable to marine diesel

¹¹Federal Register, Vol. 58, No. 93, p. 28816.

engines.

Effective 01 October 1993 highway diesel fuel must comply with a maximum sulfur content standard of 0.05 percent by weight. California has extended the EPA low sulfur requirement to include fuel sold for marine applications. The sulfur problem should be substantially resolved by specification for low sulfur fuel.

Table 1-6: CARB 1995 Marine Vessel Proposed Diesel NO_x Emission Standards (ppm)¹²

Application	Load	Baseline	Proposed	% Reduction
New Engines				
Main Propulsion	≥ 25%	650-1,200	130	78-89
Main Propulsion	< 25%	*	450	*
Auxiliaries	*	600-1,200	600	0-50
Existing Engines				
Main Propulsion	*	600-1,680	600	0-64
Auxiliaries	*	650-1,200	750	0-38

The development of a marine test procedure is vital for providing repeatable emission data. Several duty cycles have been proposed to accomplish this. However, the unique operation of U.S. Naval ships has not yet been properly modeled.

1.6 Diesel Engine Duty Cycles

Regardless of the regulatory strategy adopted by federal or state

¹²State of California, p. 13.

governments, the relationship between the operation of marine vessels and ambient air quality must be understood. Section 206 of the CAA requires the administrator of the EPA to test new engines for compliance with existing emission standards. Although marine engines are not currently regulated by EPA, duty cycles have been developed for marine vessels and are being evaluated for EPA certification.

Certified duty cycles have been developed for both highway and nonroad applications. These tests provide repeatability, wide applicability, and simplicity in modeling engine operating profiles. There are two distinct types of duty cycles; constant volume sampling (CVS) used for transient testing, and mode testing used for steady state. The CVS test uses a bag collection device. Mode testing relies upon raw gas stream measurement.

The contribution of transient operation to total emission levels is currently being investigated. Information to date suggests that transients may not be critical in most emission measurement schemes. EPA analysis of their own and industry test data during normal engine operation has shown that NO_x emission levels remain relatively consistent over a range of steady state to transient operation.¹³ In developing a duty cycle for recreational marine engines, the International Council of Marine Industry Associations (ICOMIA) provided evidence that transient operation encompasses only a small fraction (1-2%) of total operating time. This was interpreted as a result of a small number of

¹³Federal Register, Volume 58, No. 93, p. 28820.

throttle changes.¹⁴ The data analyzed for this thesis agrees with the ICOMIA data. One is led to the conclusion that understanding steady-state conditions is far more important than transient conditions in duty cycle development and testing.

Acceleration transient testing conducted on the U.S. Coast Guard Cutter *POINT TURNER* in the fall of 1993, indicated that maximum NO_x and CO levels are not that much different than the steady state condition at the higher power level. In this testing the engines were accelerated from the clutched mode (180 shaft rpm, 5 horsepower), to 650 shaft rpm and roughly 580 horsepower. During the transient, NO_x, as measured in ppm_v at 1 second intervals with a ENERAC model 2000E Portable Emissions Analyzer, was found to first decrease substantially before building up to the steady state value. CO was found to first increase at a fast rate, then gradually to attain the steady state value. The results observed are consistent with transition from steady state while clutched, to fuel rich during the first part of acceleration, and restoration of the steady state fuel/air ratio at the end of the transient event.

The results of emission testing may be reported either as a maximum single-point or as a weighted average over an operating profile. Maximum single-point measurements indicate worse case operation. This point may be measured outside of the normal operating range of the engine tested. The

¹⁴Edward J. Morgan, "Duty Cycle for Recreational Marine Engines," SAE Paper No. 901596, 1990, p. 10.

proposed marine emission levels described in Table 1-6 are of the maximum single-point type. These levels are reported based on volumetric flow rate (ppm_V), maximum brake specific mass level, or as the emission index given in grams per kilogram of fuel. The weighted average method tests the engine over a profile of varying loads and speeds. This method obtains a more accurate estimation of engine emissions as a function of power produced (g/bhp-hr). An accurate engine operating profile is required for the weighted average method. The weighted average method is preferred since it provides an indication of emissions over the actual operating range of the engine.

Several duty cycles have been proposed for marine vessels. Each duty cycle specifies speed/power combinations with factors indicating time percentage at that combination. Duty cycles are classified as Ψ -Mode; Ψ indicates the number of combinations tested. Duty cycles with a greater number of combinations (Ψ) provide greater emission/efficiency detail. However, the selection of speed/power and time in mode must be done carefully so as to accurately reflect actual operation. If poorly performed, data will not be representative of actual operating conditions.

1.6.1 DEMA Duty Cycle

The predecessor of the Engine Manufacturers Association (EMA), the Diesel Engine Manufacturers Association (DEMA), published a 3 mode duty cycle in 1974. Although no longer supported by EMA, the duty cycle provided an early attempt to model a generator engine operating profile. This duty cycle assumes

constant speed operation and is provided in Table 1-7.

Table 1-7: DEMA Duty Cycle¹⁵

Cycle Point	Specified Load, %	Time Factor
1	50	0.2
2	75	0.4
3	100	0.4

1.6.2 ICOMIA Standard No. 36-88

ICOMIA Standard Number 36-88, Marine Engine Duty Cycle, provides a 5-mode duty cycle for recreational and commercial marine engines. Table 1-8 gives this duty cycle. This cycle emphasizes low speed/torque operation which may be applicable to U.S. Navy ships maneuvering in a harbor or when conducting on-station duties just over the horizon from shore.

Table 1-8: ICOMIA Marine Engine Duty Cycle (Standard No. 36-88)¹⁶

Mode	Engine Speed*	Engine Torque*	Time Factor
1	Idle	0	0.40
2	0.4	0.253	0.25
3	0.6	0.465	0.15
4	0.8	0.716	0.14
5	1.00	1.000	0.06

Note: * As a fraction of engine rating.

¹⁵Naval Sea System Command, 1991, p. 6-10.

¹⁶Edward J. Morgan and Richard H. Lincoln, "Duty Cycle for Recreational Marine Engines", SAE Paper 901596, 1990, Appendix 2.

1.6.3 EPA 13-Mode Duty Cycle

The 13-Mode EPA Duty Cycle has been used for several years for standardized steady state heavy-duty diesel engine emission testing. Table 1-9 gives the EPA 13-Mode Duty Cycle.

Table 1-9: EPA 13-Mode Duty Cycle¹⁷

Mode	Engine Speed	Engine Torque*	Time in Mode		Time Factor
			Min.	Max.	
1	Idle	0	4.5	6	0.067
2	Intermediate	2	4.5	6	0.08
3	Intermediate	25	4.5	6	0.08
4	Intermediate	50	4.5	6	0.08
5	Intermediate	75	4.5	6	0.08
6	Intermediate	100	4.5	6	0.08
7	Idle	0	4.5	6	0.067
8	Rated	100	4.5	6	0.08
9	Rated	75	4.5	6	0.08
10	Rated	50	4.5	6	0.08
11	Rated	25	4.5	6	0.08
12	Rated	2	4.5	6	0.08
13	Idle	0	4.5	6	0.067

Note: *Percent of Maximum Observed

The EMA and Economic Commission for Europe (ECE) have proposed alternatives to the weighting (time) factors for the standard U.S. EPA 13-Mode

¹⁷ibid., p. 6-7.

Duty Cycle for nonroad applications. Table 1-10 provides this comparison.

Table 1-10: Nonroad Weighting Factors v. EPA 13-Mode Duty Cycle¹⁸

Mode	Time Factors (%)		
	U.S. EPA	ECE 49	EMA
1	20/3	25/3	15
2	8	8 (10 % Load)	0
3	8	8	0
4	8	8	10
5	8	8	10
6	8	0	10
7	20/3	25/2	0
8	8	8	15
9	8	8	15
10	8	8	15
11	8	8	0
12	8	8 (10% Load)	10 (10% Load)
13	20/3	25/3	0

1.6.4 Japanese Heavy-Duty Diesel Duty Cycle

Japan has established itself as a major contributor in heavy-duty diesel engine research and development. They have developed a six mode duty cycle for engine testing, Table 1-11. This duty cycle emphasizes higher engine speed and heavier loading conditions than the standard EPA 13-Mode. It does not test full load at rated speed.

¹⁸Ibid. p. 6-12.

Table 1-11: Japanese Heavy-Duty Diesel Duty Cycle¹⁹

Mode	Engine Speed (% of Rated)	Engine Load (% of Rated)	Time Factor (%)
1	Idle	0	3.5
2	40 or 1000 rpm	100	7.1
3	40 or 1000 rpm	25	5.9
4	60	100	10.7
5	60	25	12.2
6	80	75	28.6

1.6.5 U.S. Navy Endurance Test

The U.S. Navy procures medium speed heavy-duty diesels subsequent to successful completion of the 1,000 hour endurance test, comprised of 125 eight hour cycles. Although emission measurements are not taken concurrent with this test, steady state readings could be made. The data would not reflect inservice emission levels unless the durability test were modified to conform to the individual ship application operating profile. Table 1-12 gives the U.S. Navy durability test cycle (8 hour).

¹⁹Ibid., p. 6-13.

Table 1-12: U.S. Navy Medium Speed Diesel Engine Endurance Test²⁰

Mode	Time (minutes)	Time Factor	Engine Load (% of Rated)	Engine Speed (% of Rated)
1	120	0.250	100	100
2	60	0.125	85	100
3	10	0.021	0	Idle
4	110	0.229	100	100
5	10	0.021	0	Idle
6*	30	0.063	50	75 (Reverse)
7	10	0.021	0	Idle
8	10	0.021	85	100
9	110	0.229	110	100
10	10	0.021	0	Shutdown

Note: *For main propulsion engines, for constant speed engines (SSDG) 50% load at rated speed in the forward direction.

1.6.6 ISO 8178-4 Duty Cycles

The International Organization for Standardization (ISO) published its draft proposal "Reciprocating Internal Combustion (RIC) Engines - Exhaust Emission Measurement", ISO 8178, in May of 1992. ISO 8178 is a five part procedure designed to standardize engine exhaust measurement. Part four provides 13 duty cycles for different engine applications. The EPA is currently evaluating ISO 8178 for use in the United States. Table 1-13 gives the 13 duty cycles, and Table 1-14 defines them.

²⁰Military Specification, "Engines, Diesel Marine, Propulsion and Auxiliary, Medium Speed," MIL-E-23457B, March 1976, p. 23.

Table 13: ISO 8178-4 RIC Duty Cycles²¹

T E S T	Idle	60 Percent of Rated Speed					Rated Speed				
	Percent Load										
	0	10	25	50	75	100	10	25	50	75	100
A	0.25	0.08	0.08	0.08	0.08	0.25	0.02	0.02	0.02	0.02	0.10
B	0.25	0.08	0.08	0.08	0.08	0.25	0.02	0.02	0.02	0.02	0.10
C1	0.15	*	*	0.10	0.10	0.10	0.10	*	0.15	0.15	0.15
C2	0.25	*	0.38	*	*	0.07	0.23	*	*	*	0.07
D1	*	*	*	*	*	*	*	*	0.20	0.50	0.90
D2	*	*	*	*	*	*	0.10	0.30	0.30	0.25	0.05
F	0.60	*	*	0.15	*	*	*	*	*	*	0.25
G1	0.05	0.07	0.30	0.25	0.20	0.09	*	*	*	*	*
G2	*	*	*	*	*	*	0.07	0.30	0.29	0.20	0.09
G3	0.10	*	*	*	*	*	*	*	*	*	0.90
E1	0.40	*	0.25	0.15	0.14	*	*	*	*	*	0.06
E2	*	*	*	*	*	*	*	0.15	0.15	0.5	0.2
E3	% Speed/ % Load/ Weight			63/25/0.15		80/50/0.15		91/75/0.50		100/100/ 0.20	

The series E duty cycles have been proposed for marine application.

Cycles E2 and E3 are applicable to U.S. Navy ships with diesel main propulsion engines. Both are four mode tests that do not adequately cover the light loading condition common to near land operation. Cycle D1, a three mode duty cycle, applicable to power generation plants, does not cover the low load ranges that

²¹ISO 8178-4, and Naval Sea Systems Command, p. 6-15.

Table 1-14: ISO 8178 Duty Cycle Definitions

Cycle	Description
A	Reference cycle for vehicle engines.
B	Universal cycle, applications similar to on-road vehicle service.
C1	Off-road vehicles and industrial equipment, medium and high load.
C2	Off-road vehicles and industrial equipment, low load.
D1	Constant speed applications, power plants.
D2	Constant speed applications, generator sets with intermittent load.
E1	Marine engine applications, pleasure craft engines.
E2	Marine engine applications, constant-speed engines for ship propulsion.
E3	Marine engine applications, heavy-duty propulsion engines.
F	Locomotive applications.
C1	Small engines, utility lawn and garden.
G2	Small engines, utility lawn and garden.
G3	Small engines, handheld equipment.

typify shipboard SSDG lineups for maximum redundancy/reliability. ISO 8178 has attempted to cover the entire spectrum of RIC engines in use throughout the world. However, what may be applicable for commercial shipping is not valid for military vessels. Therefore, a need exists for additional duty cycles that provide a reliable naval warship operating profile.

1.6.7 CARB 8-Mode Duty Cycle

In 1990 CARB introduced an eight-mode duty cycle that measured engine emissions under high loading conditions. Each mode of the CARB cycle was held for three minutes of steady operation and sufficient time was allowed

between points to stabilize the next condition. This duty cycle provided a good indication of engine emissions under steady state and high load conditions.

Table 1-15 gives the CARB duty cycle.

Table 1-15: CARB 8-Mode Duty Cycle²²

Mode	Engine Speed	Engine Load (% of Rated)	Time Factor
1	Idle	0.00	0.05
2	Rated	0.75	0.15
3	Rated	0.50	0.15
4	Idle	0.00	0.05
5	Max. Torque	1.00	0.15
6	Max. Torque	0.75	0.15
7	Max. Torque	0.50	0.15
8	Max. Torque	0.30	0.15

The time factors listed in Table 1-15 are estimates based upon the ISO 8178-4 C1 Duty Cycle which superseded the CARB 8-Mode Duty Cycle. The CARB time factors were not available for inclusion in this thesis. CARB is in the process of evaluating the ISO 8178-4 Duty Cycles for adoption into the CARB program. Evaluation is expected to be completed in 1995 with rule making expected shortly thereafter.

²²Paul Stiglic, et. al., "Emission Testing of Two Heavy Duty Diesel Engines Equipped with Exhaust Aftertreatment," SAE Paper 900919, 1990, p. 5.

1.7 Thesis Methodology and Scope

This thesis developed alternative diesel engine duty cycles for naval ships based upon the LSD 41 Class. Duty cycles were devised for both main propulsion engines and ship service diesel generator engines. Of the eight landing-ship-dock variant ships of the LSD 41 Class currently in commission, four were visited for the purpose of log review. Appendix B gives the details of the ship visits conducted for data collection.

Each ship maintains Deck Logs (general ship operation), Engineering Smooth Logs (engineering plant general operation), Engineering Bell Logs (speed change), and Diesel Engine Operating Logs for up to three years. From the information contained in these logs, a ship operating profile was developed. Together with the operating profile, additional information in the form of meteorological, tidal, hull powering requirements, operator preference, scheduled maintenance, inspection reports, and ship specifications was synthesized to generate the two naval diesel duty cycles. Once the duty cycles were written, comparisons were made using data available in the literature describing diesel engine exhaust emissions as a function of speed and power.

After completing the duty cycle portion of this thesis, a study was performed resulting in a recommended stack emission testing methodology. In this work, the ambiguities resulting from turbulent gas flow were accounted for by engineering approximations and modeling.

CHAPTER 2: LSD 41 CLASS OPERATING PROFILE DEVELOPMENT

2.1 LSD 41 Class Description

2.1.1 Hull Naval Architecture Description

The LSD 41 Class design is based on the earlier *ANCHORAGE* Class (LSD 36) of ships. Figure 5 is a port bow view of the *USS WHIDBEY ISLAND* (LSD 41) at sea. Figure 6 provides the LSD 41 Class body plan, which consists of two half transverse elevations or end views of the ship; both have a common

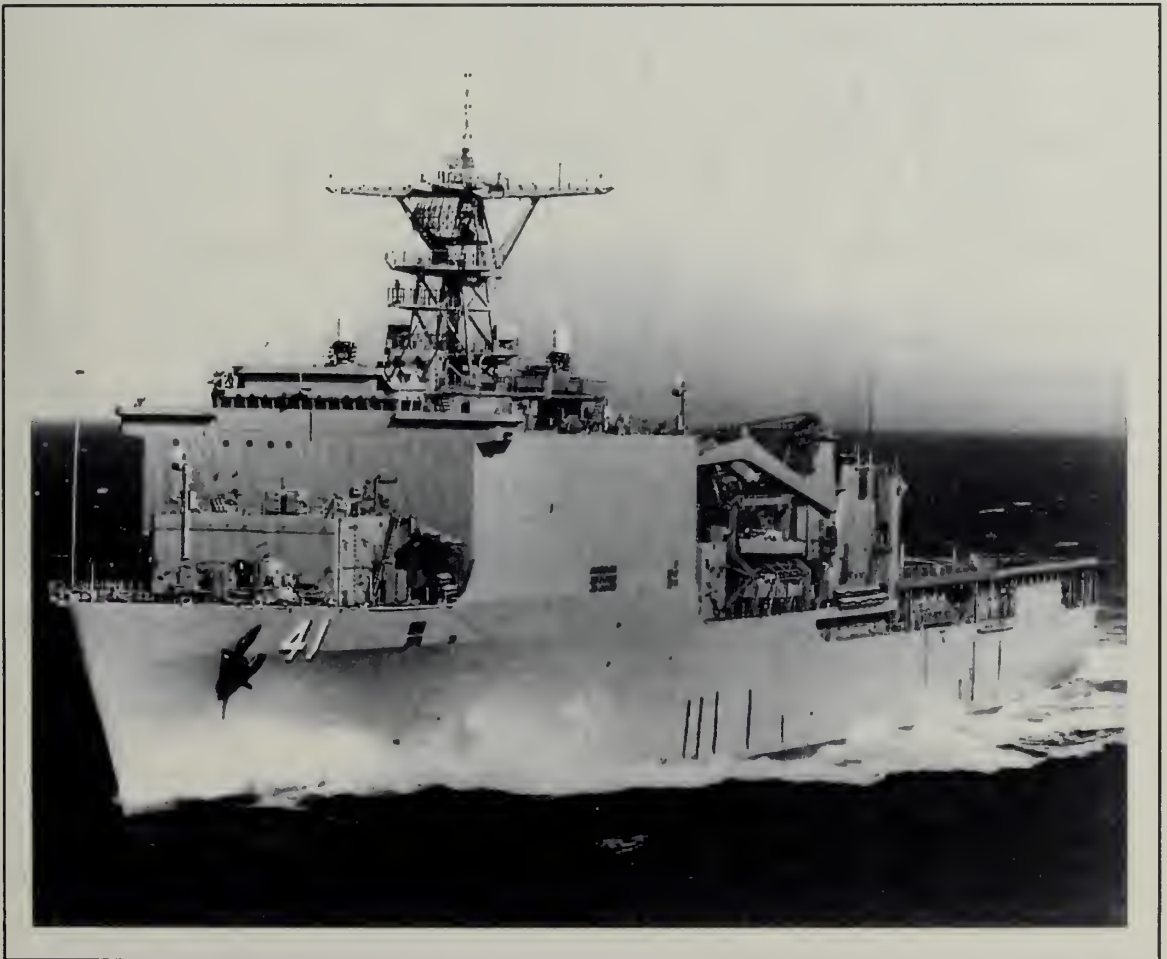


Figure 5: *USS WHIDBEY ISLAND* (LSD 41)

vertical centerline. The right-hand side of Figure 6 represents the ship as seen

from ahead, the left-hand side as seen from the stern. The body plan indicates the cross sectional shape of the ship. This shape directly impacts wetted surface area and, therefore, ship powering requirements. Principle dimensions of the LSD 41 Class are provided in Table 2-1.

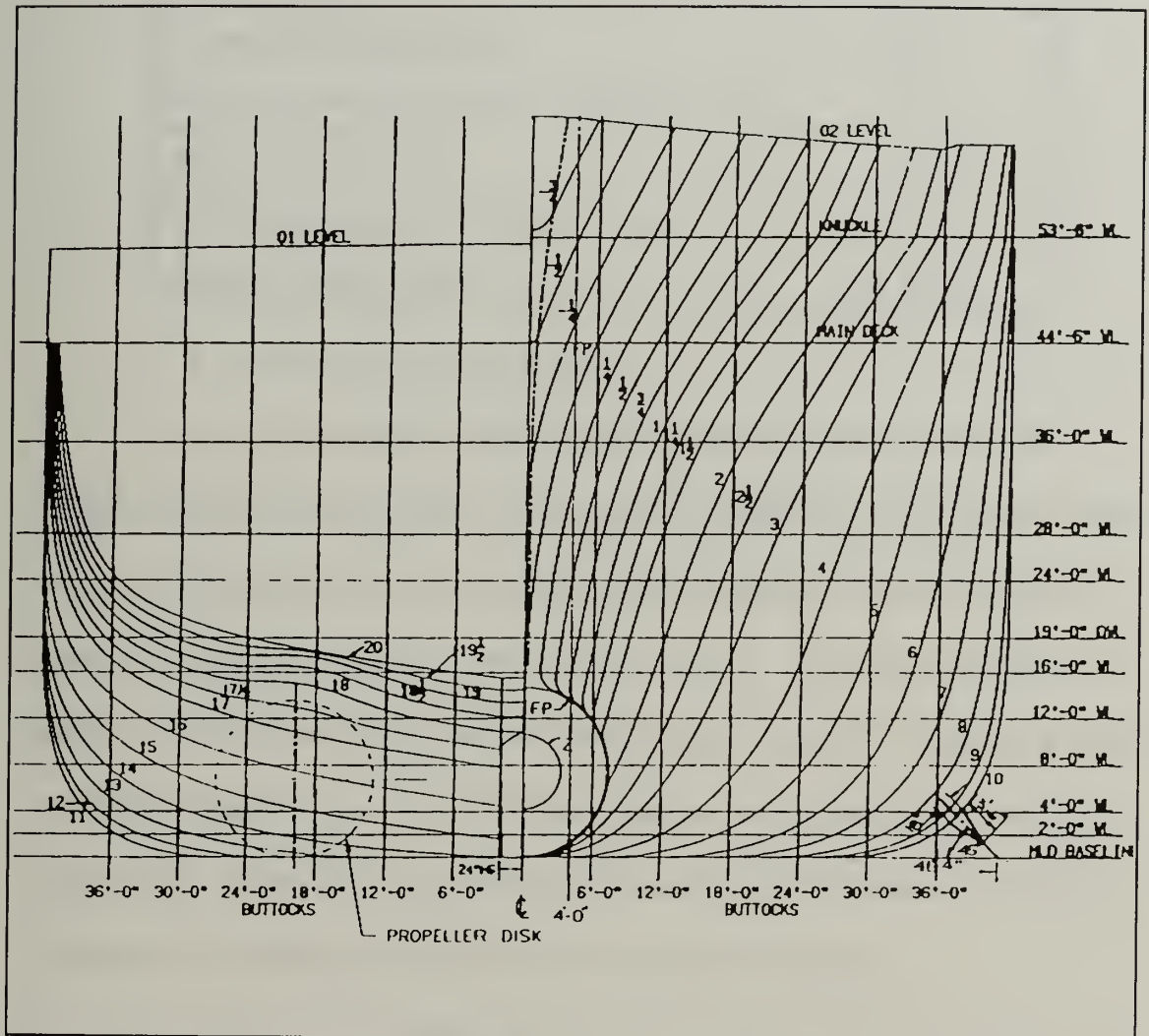


Figure 6: LSD 41 Class Body Plan

Table 2-1: LSD 41 Class Principle Hull Dimensions

Design Displacement	15,745 ltons
Length Overall	609.58 ft
Length Between Perpendiculars	580 ft
Extreme Beam	84 ft
Design Draft	19 ft
Prismatic Coefficient (C_p)	0.612
Maximum Midship Section Coefficient (C_x)	0.945
Block Coefficient (C_B)	0.578
Waterplane Area Coefficient (C_{WP})	0.779
Wetted Surface Area	50,100 ft ²

2.1.2 Propulsion Plant Description

The LSD Class has two shafts. Each shaft is powered by two Colt-Pielstick 16PC2.5V four stroke, turbocharged, intercooled, non-reversing diesel engines. Each diesel must be connected to the Philadelphia Gear reduction gear via pneumatic clutch in order to transmit power. The reduction gear is a locked train single reduction gear with two drive pinions, each clutched to a main propulsion diesel engine. The reduction gear reduction ratio (Δ) is given by equation (2). Power is transmitted into the water via twin 5-bladed, 13.5 foot diameter Bird-Johnson controllable-reversible pitch propellers.

$$\Delta = \frac{RPM_{Diesel}}{RPM_{Shaft}} = 3.1515 \quad (2)$$

The Colt Pielstick 16PC2.5V design output is 10,400 brake horsepower (bhp) at air inlet temperature of 51° Celsius. As part of the naval qualification

process diesel engines must produce rated power over a wide temperature range. U.S. Navy specifications call for an operating temperature range of -84° to 60° Celsius. Qualification for U.S. Navy shipboard application required derating the engine by 18% to 8,500 bhp at 520 revolutions per minute (RPM). The shaft torque limits of 262,000 ft-lbs for single engine, and 525,000 ft-lbs for dual engine operation are not exceeded at rated engine operation. The ship is torque limited since at rated RPM rated power is not achieved. To achieve rated power, propeller pitch is adjusted to approximately 70 percent pitch. Basic engine parameters are given in Table 2-2.

Power is lost due to component friction where power is transmitted from the prime mover to the propeller. Mechanical efficiency (η_{MECH}) is the relation between shaft horsepower (shp) measured at the propeller and brake horsepower measured at the prime mover output shaft. Equation (3) provides this relation for the LSD 41 Class.

$$\eta_{MECH} = \frac{SHP}{BHP} = \frac{33,000}{34,000} = 0.971 \quad (3)$$

Table 2-2: Main Propulsion Diesel Engine Parameters

Model	Colt-Pielstick, PC V
Type	Non-Reversing
Cycle	Four Cycle, Turbocharged
Rated Load	8,500 BHP
Rated RPM	520
Minimum Engine Idle	200 RPM
Bore and Stroke - mm	400 x 460
Number of Cylinders	16
Piston Displacement	57.8 Liters
Combustion Chamber Volume	5.51 Liters
Compression Ratio	11.5:1
Equivalence Ratio @ Rated	0.38
bmeP @ Rated Conditions	1,934.7 kPa
Piston Speed @ Rated RPM	7.98 m/sec

2.1.3 Ship Service Diesel Generator Description

Ship service electrical power is provided by four 1,300 kW generators, each driven by a Fairbanks Morse 38ND8-1/8 opposed piston diesel engine. These engines are constant speed of 720 RPM. Basic ship service diesel engine parameters are given in Table 2-3.

When underway the ship electric plant is in a parallel configuration, normally with two diesel generators running. Nominal underway ships electric load is approximately 1,300 kW at 1,500 amps. The average load on each machine, with two engines running, gives a load of about 50 percent of rated capacity. Operation of cranes, anchor windlass, and ballast compressor motors

often requires starting an additional diesel generator to provide starting surge capacity. Starting surges are significant, the highest surges are those of the ballast air compressors at 400 amps. Low loading causes glazing of the cylinder liners and build up of carbon deposits. As a result, the diesel prime movers are maintenance intensive.

Table 2-3: Ship Service Diesel Engine Parameters

Model	Fairbanks Morse 38ND8-1/8
Type	Opposed Piston
Cycle	Two Cycle, Turbocharged
Engine Rated Load	1,837 BHP (@ 0.8 p.f.)
Rated Generator Capacity	1,300 kW
Rated RPM	720
Minimum Engine Idle	525 RPM
Bore and Stroke - mm	206.4 x 254
Number of Cylinders	12
Piston Displacement	17.0 Liters
Compression Ratio	16.1:1
Equivalence Ratio @ Rated	0.35
bmeP @ Rated Conditions	559.9 kPa
Piston Speed @ Rated RPM	6.10 m/sec

2.2 Ship Powering

The ship propulsion plant must provide sufficient power to overcome the resistance to forward motion. This resistance, or drag, is composed of two primary flow mechanisms; frictional resistance and residuary resistance. Frictional resistance is the largest single contributor to total ship resistance. Experiments have shown it accounts for 80 to 85 percent of total resistance in slow-speed ships and 50 percent in high-speed ships.²³ Air resistance created by the above water portion of the ship also creates drag. Environmental effects in the form of wind, waves, currents, biologic fouling of the hull, and corrosion of the hull magnify the effect of frictional resistance, increasing the power required for a given speed.

Residuary resistance is made up of wave making resistance and eddy resistance. As a ship moves through the water a surface wave system is created. The energy expended by the ship in producing this wave system is called wave making resistance. Eddy resistance refers to the energy that is lost as vortices are produced and shed from appendages such as: propeller shafts, shaft struts, rudders, and ship stern.

At slow ship speeds frictional resistance predominates. At higher speeds the effect of residuary resistance becomes most important. Frictional resistance and residuary resistance are additive. For speed-to-length ratios of less than

²³Principles of Naval Architecture Volume II - Resistance, Propulsion and Vibration, SNAME 1988, p. 7.

about 0.6, frictional resistance is dominant; above 0.6, wave making becomes dominant. For the LSD 41 Class this corresponds to a ship speed of about 12-14 knots. In the frictional regime, viscous forces dominate and resistance is proportional to velocity squared. In the residuary regime, inertial forces dominate and resistance is proportional to velocity cubed.

Ship powering requirements are determined by scale model tests and through analytic procedures. Scale model tests are conducted in both still water, and rough water to simulate heavy seas. In calculating the required installed power, predictions are made for the effect of sea state, wind, currents and other environmental effects. Once the ship has been built, it is taken to sea for a series of trials to test the performance of each installed system under actual operating conditions. One trial tests the performance of the propulsion plant. Propulsion plant Standardization Trials of *USS WHIDBEY ISLAND* (LSD 41) were conducted from 28 March to 1 April 1985 off the coast of La Jolla, California. Standardization Trials establish the relation between ship speed and propulsion plant parameters. Table 2-4 gives a summary of the important Standardization Trial parameters averaged over three runs at each speed. Frictional resistance is related to the amount of wetted surface area of the hull. Ships are operated at various conditions of loading which effect the displacement and wetted surface area of the ship. Standardization Trials were conducted at the design displacement. Design displacement is assumed throughout this thesis in determining powering requirements.

Table 2-4: Standardization Trial Results²⁴

Speed (knots)	Shaft RPM	Torque (lbf-ft)	Power (hp)
11.4	81.6	232,900	3,620
14.0	100.8	332,200	6,380
19.6	121.1	477,000	11,000
19.2	140.7	638,200	17,100
19.6	142.1	673,200	19,590
20.1	150.0	721,300	20,600
21.2	150.0	811,500	24,630
21.8	165.8	885,900	27,960

The LSD 41 Class operates over two distinct speed ranges. At speeds below 10 knots the ship speed is controlled by propeller pitch. At speeds above 10 knots ship speed is controlled by shaft RPM. In the pitch controlled regime the shaft is operated at a constant 64 RPM and speed is varied by changing the pitch of the propeller. Above 10 knots propeller pitch is set at 100 percent and speed is varied by shaft RPM. The data points presented in Table 2-4 are at 100 percent propeller pitch. Within the two regimes a mostly linear relation between pitch/rpm and speed exists. Figure 7 gives the relation in the ahead direction, and Figure 8 in the astern direction.

²⁴Everett I. Woo and Michael L. Klitsch, "USS WHIDBEY ISLAND (LSD 41) Standardization, Trained and Locked Shaft Trials," David W. Taylor Naval Ship Research and Development Center, December 1985, p. 26.

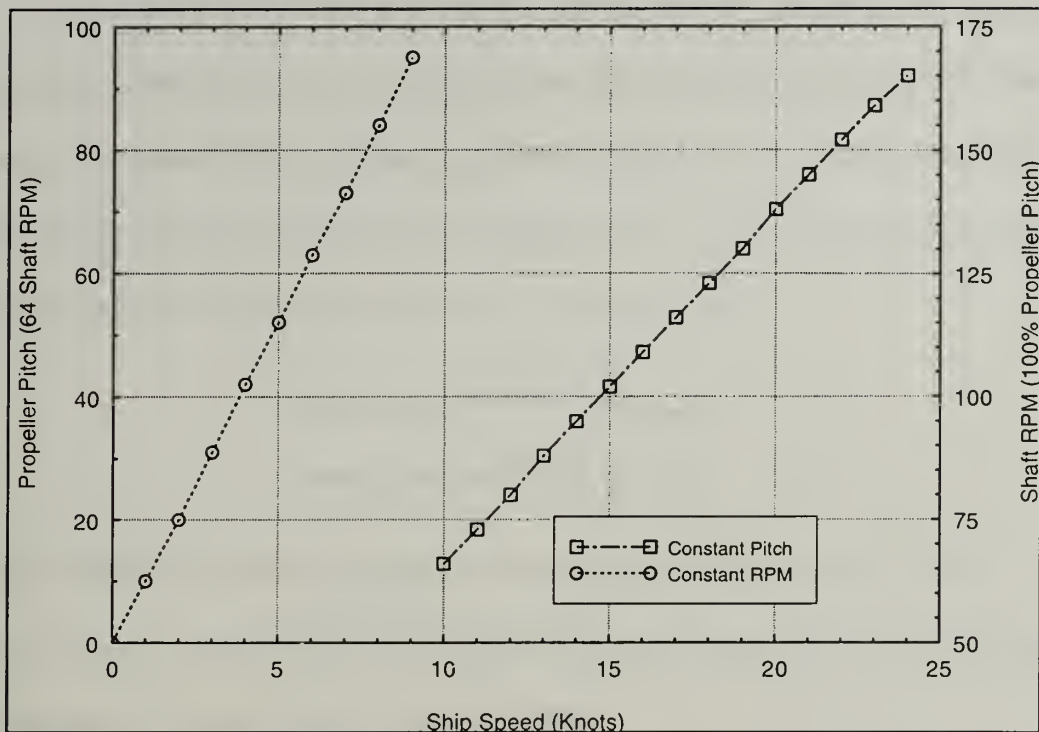


Figure 7: Ship Speed Ahead vs. RPM

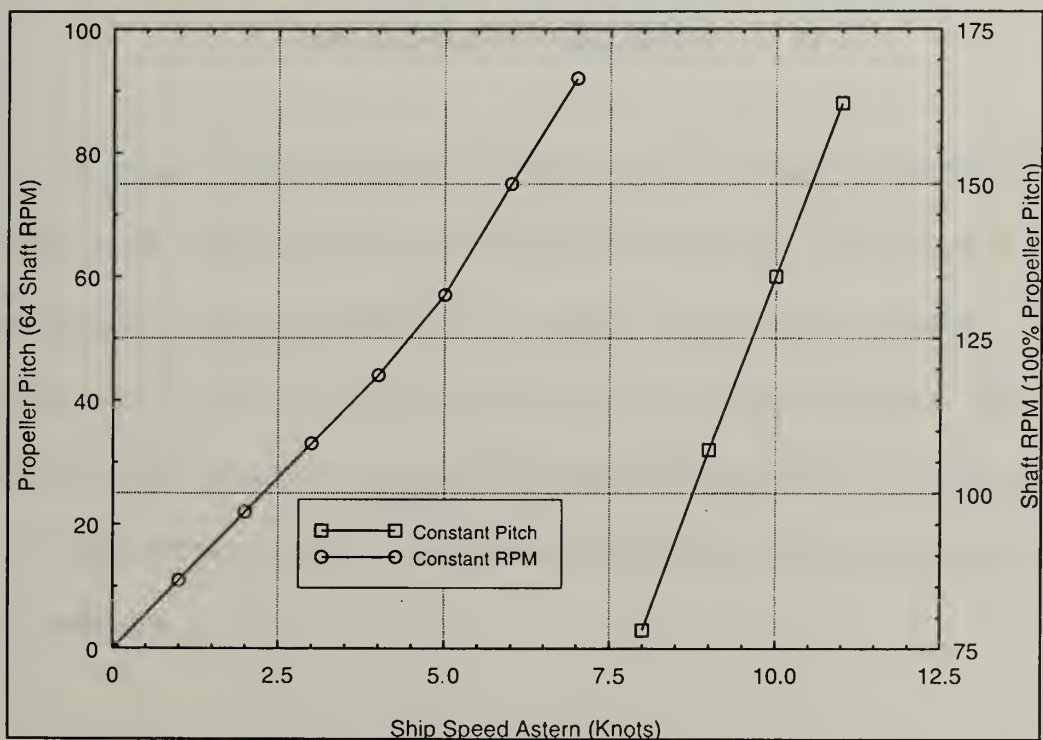


Figure 8: Ship Speed Astern vs. RPM

The two curves of Figure 7 may be represented by equations for straight lines. Ship speed is either linearly dependent on propeller pitch or shaft RPM. Equation (4) gives the ship speed equation for operation in the constant RPM region where speed is governed by propeller pitch. Equation (5) gives the ship speed equation for operation in the RPM controlled region.

$$Speed_{ship} = 0.0948 \times Pitch_{Propeller} \quad (4)$$

$$Speed_{ship} = 0.143 \times RPM_{Shaft} + 0.571 \quad (5)$$

Similar equations describe the astern speed dependence on pitch or RPM shown by the curves in Figure 8. Equation (6) gives the pitch controlled relation, and equation (7) gives that controlled by RPM.

$$Speed_{ship} = 0.076 \times Pitch_{Propeller} \quad (6)$$

$$Speed_{ship} = 0.035 \times RPM_{Shaft} + 5.23 \quad (7)$$

The greater power required to move the ship in the astern direction is reflected in the slopes of the curves of Figure 7 and Figure 8. The slope of the ahead direction curves is greater than the astern slopes due to a greater responsiveness of the ship to propulsion forces in the ahead direction. The shape of the bow presents a streamlined shape which requires less energy to move. The blunt stern section behaves as a bluff body and has a much higher drag coefficient.

The data in Table 2-5 suggests the relation between speed and power for the LSD 41 Class under the conditions given. Curve fitting the speed and shaft power data provides the speed vs. power graph given in Figure 9.

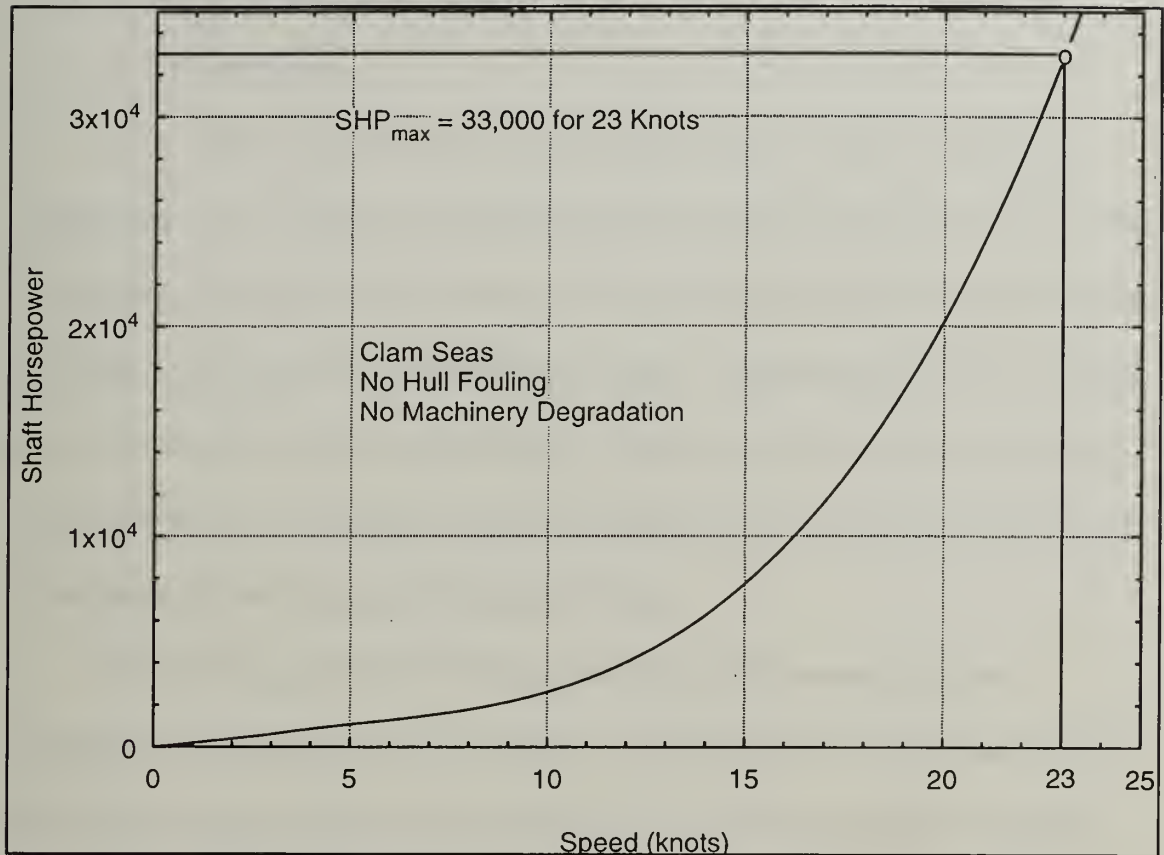


Figure 9: LSD 41 Class Speed Power Curve

The curve of Figure 9 is a combination of two curves covering the two resistance regimes. The frictional regime is represented by equation (8) and the residuary regime is given by equation (9). Equation (8) is valid up to 12 knots, and equation (9) is valid from 10 to 25 knots. The overlap of 2 knots indicates a transition from frictional to residuary resistance control.

$$Power = 9.6 \times Speed^2 + 172 \times Speed \quad (8)$$

$$Power = 5.04 \times Speed^3 - 79.7 \times Speed^2 + 621 \times Speed - 674 \quad (9)$$

2.3 Characteristics of Ship Operation

2.3.1 Ship Logs

U.S. Naval ships record a variety of information in official log books.

These logs form a record of all significant ship events throughout its service life. This thesis reviewed two logs in detail. The information gained from log review was used to develop the class operating profile. Logs analyzed were the ships Deck Log and Engineering Smooth Log. Other logs such as engine operating log data sheets and navigation logs were examined to correlate the data found in the Deck Log and Engineering Smooth Log.

The Deck Log provides a historical record of all events deemed noteworthy throughout the life of the ship. The Deck Log records events such as: ship handling training, drills, casualties, maintenance actions, underway replenishment, underway refueling, landing craft air cushion (LCAC) operations, flight operations, major equipment trend analysis, special propulsion plant evolutions as well as information giving course, speed, distance from land and weather conditions. The time and order given for each change in engine speed and ships course are recorded in the ships Deck Log. Speed change orders are given in terms of bell order, followed by propeller pitch or shaft RPM (depending on the ship speed regime). Tables 2-5 and 2-6 show the relation between bell

Table 2-5: Ahead Bells

Bell Order	Speed (knots)	Shaft RPM	Propeller Pitch
All Stop	0	64	0
1/3	1	64	10
1/3	3	64	20
1/3	3	64	34
1/3	4	64	42
1/3	6	64	52
1/3	6	64	63
1/3	7	64	73
1/3	8	64	84
1/3	9	64	95
2/3	14	66	100
2/3	11	73	100
2/3	12	80	100
2/3	13	88	100
2/3	14	95	100
2/3	15	152	100
Standard	16	145	100
Standard	14	116	100
Standard	14	123	100
Standard	19	130	100
Full	20	138	100
Full	20	145	100
Flank	22	152	100
Flank	23	159	100
Flank	24	165	100

and shaft operation for ship speeds in the ahead and astern direction. The Deck Log is maintained as a legal record. It is the most important log kept aboard a ship. A sample Deck Log sheet is given in Appendix A.

Table 2-6: Backing Bells

Bell Order	Speed (knots)	Shaft RPM	Propeller Pitch
1/3	1	64	11
1/3	2	64	22
1/3	3	64	33
1/3	4	64	44
2/3	5	64	57
2/3	6	64	75
2/3	7	64	92
Full	8	78	100
Full	9	107	100
Full	10	135	100
Full	11	163	100

The Engineering Smooth Log records information similar to that found in the Deck Log. However, the Engineering Smooth Log only records information related to the engineering plant. Starting and stopping a major piece of equipment, clutching an engine into the reduction gear, shifting engine speed control to a remote location such as the pilot house, maintenance actions, equipment malfunction and failure, status of auxiliary systems, lube oil purification, fuel transfer and other activities are recorded in the Engineering Smooth Log. A sample Engineering Smooth Log sheet is given in Appendix A.

Engine operating logs record hourly engine speed, temperatures and pressures. These logs provide an indication of total time in operation, and abnormal, or out-of-specification conditions. Operating logs are also used to record engine parameters during trend analysis. An operating log is maintained for each operating engine. A sample log sheet is given in Appendix A.

Navigation logs record the position of the ship on an hourly basis according to position fixes. Position fixes plotted on a navigation chart indicate the track over which a ship traversed. Distances from land are readily determined from track information.

2.3.2 Operator Preference

Operator preference is the single most important factor governing the operating profile of main propulsion engines. Operator preference refers to the skill, training level, and aggressiveness of those navigating the ship and responding to engine speed change orders. The skill and training level of the navigation team becomes apparent through review and comparison of the Deck Log entries for similar ship evolutions, such as, anchoring, getting underway from a pier, and mooring to a pier. More highly skilled teams will have fewer number of speed changes over the course of the evolution.

Aggressiveness is difficult to quantify, but refers to the level of dexterity demonstrated in how a ship is operated. An aggressive navigation team may not use tug boats in getting underway or mooring to a pier. The time required to perform these evolutions may also be minimized, reducing time engines are

operated at low load or at idle.

Ship port departure speed is subject to the preference of the navigation team led by the ships commanding officer. The amount of redundant equipment in operation is also largely a matter of preference. Experience shows accident boards are more forgiving of ship captains who prepared for potential problems by having equipment ready to instantly come on line should a casualty occur. This tendency for equipment redundancy may be prudent for vessel operation, but results in lightly loaded equipment operating for several hours.

2.3.3 Underway Ship Operations

In developing the LSD Class Operating Profile ship operating logs were reviewed to determine time factors for engine speed/loading conditions. To remain consistent with the California Coastal Waters designation of Figure 2, ship operations out to 100 nautical miles from land were recorded in the database.

Unlike commercial ships getting underway for profit, naval vessels most often get underway for training. Commercial vessels are typically operated at speed and power combinations that maximize fuel efficiency. Commercial vessels also tend to follow tracks that minimize the distance from port to port. Although naval vessels are concerned with fuel economy, efficiency is often sacrificed for speed, maneuverability, and other operational requirements.

Underway preparations usually begin several hours before the ship actually leaves port. Shore services are disconnected and the ship becomes

self-sufficient in electric power, fresh water and steam. Normally ships electric load is carried by two lightly loaded ship service diesel engines (SSDG's) . Approximately 45 minutes prior to underway time the main propulsion diesel engines (MPE's) are started. After warming up for 10 minutes they are clutched into the reduction gear, and remain at idle for the next 35 minutes on average.

Naval ships are operated most conservatively during the transit to and from sea. As a ship maneuvers from the pier through the harbor and out to sea it is most vulnerable to collision with other vessels or to grounding. Probability of an adverse action is greatly increased by failure within the propulsion or electrical plant. To decrease failure probability, redundant systems and equipment are in operation during the time that a ship transits to or from sea. A special operating condition, Sea and Anchor Detail, governed by the Restricted Maneuvering Doctrine (RMD) is manned to maximize equipment and personnel readiness. A normal Sea and Anchor Detail typically lasts for about two hours as a ship transits in and out of port.

The traditional underway usually begins with the shafts turning in opposite directions to twist the stern of the ship away from the pier. Next the shaft directions are reversed and the bow of the ship moves away from the pier. This series of engine orders may number ten bell changes over a span of five minutes. During this phase of maneuvering the engines are essentially steady-state only briefly, or mostly transient, before the next bell. Away from the pier, the ship slowly makes headway using a 1/3 bell for three to five knots. Clear of

close obstacles, ship speed is often increased to ten knots for the remainder of the transit to open water. When in open water, ship speed then becomes more discretionary for the navigation team.

Once at sea, the ship secures from the Sea and Anchor Detail and the RMD. After securing from RMD most ships typically shift engineering plant operation to maximize fuel efficiency and minimize machinery wear. The normal post RMD lineup consists of one MPE per shaft and two SSDG's in parallel. The maximum speed that can be attained by LSD 41 Class in this lineup is roughly 18 knots. Evolutions requiring more speed and power necessitate additional MPE's on the line.

U.S. Navy ships operate off the Southern California Coast in the SOCAL Operation Area, and off the Norfolk, Virginia area in the VACAPES Operation Area. These operating areas are within 100 nautical miles of land and are approximated in Figures 10 and 11. While operating in these areas ships will conduct: man overboard drills, shiphandling training, shipwide warfighting and casualty control drills, underway replenishment to resupply with fuel, ammunition and stores, flight operations, and trend analysis on MPE's and SSDG's.



Figure 10: Southern California (SOCAL) Operating Area (Approximate)

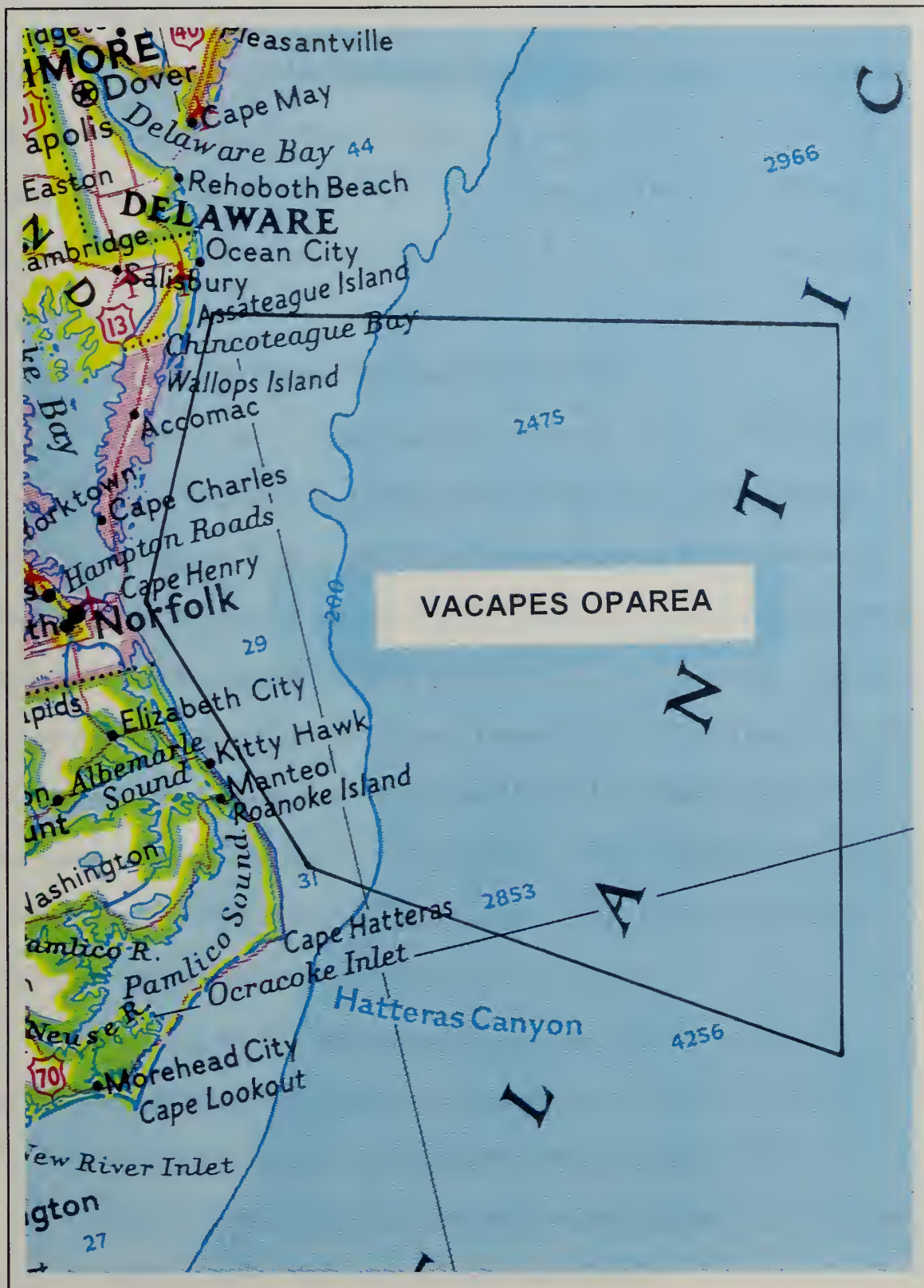


Figure 11: Virginia Capes (VACAPES) Operating Area (Approximate)

The LSD 41 Class frequently conducts amphibious assault exercises with embarked Landing Craft Air Cushion (LCAC) craft both at sea and off the coasts of southern California and North Carolina. For these operations the ship may be steaming at between 10 and 13 knots, or it may be at anchor. Each of these evolutions exercises the propulsion plant through a wide range of speed and power combinations.

2.4 LSD 41 Class MPE and SSDG Operating Profile

The wide range of operator preferences coupled with the variety of ship evolutions complicates the development of a standard naval ship operating profile. The application of commercial or civilian standards to describe naval ship operation is inappropriate. Four LSD 41 Class ships logs, covering several months of operation within 100 nautical miles of land, were analyzed. Logs of ships from the east and west coasts were reviewed to distinguish geographically related differences. Two ships were homeported in Little Creek, Virginia, and two were homeported in San Diego, California. Table 2-7 presents a summary of the operational time evaluated. Appendix B provides data summaries for: each ship, breakdown by coast, and the composite profile.

Developing the ship operating profile involved determining time of operation at specific speed and power combinations. Figure 12 provides a flowchart of the logic used in the Lotus 123W database used to perform the profile analysis. Table 2-8 gives the four ship composite operating profile of the LSD 41 Class operating within 100 nautical miles of land.

Table 2-7: LSD 41 Class Ship Data Summary (All Times in Minutes)

	LSD 43	LSD 44	LSD 46	LSD 47
Name	Fort McHenry	Gunston Hall	Tortuga	Rushmore
Coast	West	East	East	West
Time Period (1993)	12 July 16 December	14 September 30 November	3 March 20 September	1 June 16 December
Main Propulsion Engine Data				
Data Points	5,011	2,816	4,267	3,013
Time Covered	252,324	133,052	159,845	145,517
Time Secured	74,589	54,499	76,872	51,025
Time Running	177,735	78,553	82,973	94,492
Time Warmup	1,458	1,306	1,892	1,571
Time @ Idle	2,886	1,725	2,357	1,155
Time @ Power	173,391	75,522	78,724	91,766
Ship Service Diesel Engine Data				
Data Points	992	414	862	809
Time Covered	239,750	146,895	210,854	182,942
Time Secured	66,127	38,516	90,442	55,328
Time Running	173,623	108,379	120,432	127,614
Time Warmup	1,602	1,664	2,101	3,065
Time @ Idle	1,039	4515	2,329	1,275
Time @ Power	170,982	106,300	116,002	123,274

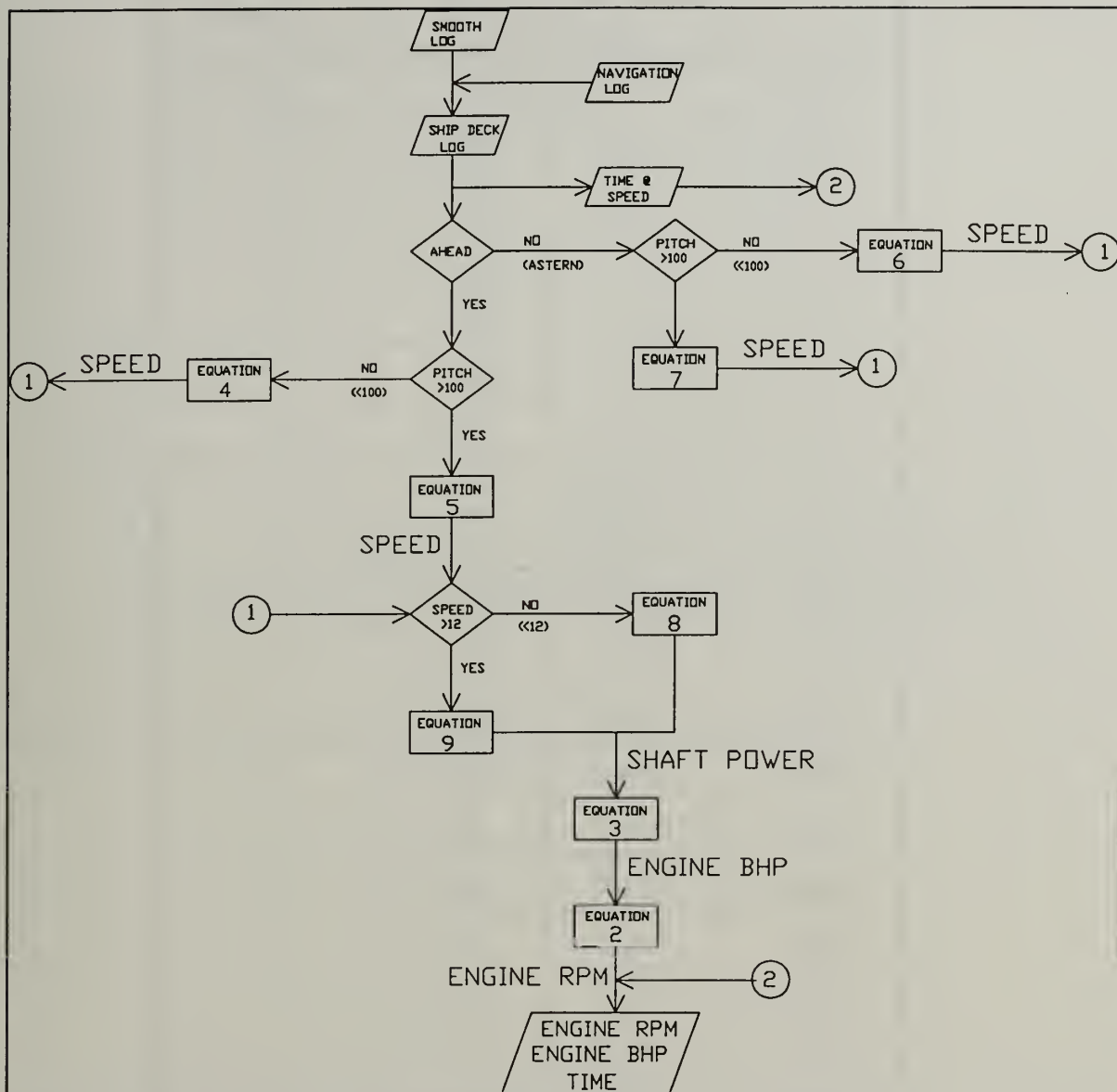


Figure 12: Operating Profile Flow Chart

Table 2-8: LSD 41 Class Composite Operating Profile Time Factors

Ship Speed (knots)	Engines/Shaft		Total
	1	2	
Idle	0.081		0.081
1	0.003	0.001	0.002
2	0.001	0.015	0.011
3	0.001	0.008	0.003
4	0.003	0.003	0.007
5	0.102	0.033	0.139
6	0.005	0.003	0.008
7	0.017	0.005	0.022
8	0.014	0.034	0.015
9	0.003	0.003	0.003
10	0.083	0.056	0.139
11	0.005	0.003	0.017
12	0.028	0.012	0.003
13	0.025	0.015	0.035
14	0.028	0.003	0.008
15	0.057	0.034	0.088
16	0.041	0.015	0.056
17	0.105	0.015	0.120
18	0.015	0.011	0.026
19	0.000	0.017	0.017
20	0.000	0.034	0.034
21	0.003	0.015	0.015
22	0.000	0.027	0.027
23	0.000	0.019	0.019
24	0.000	0.035	0.035

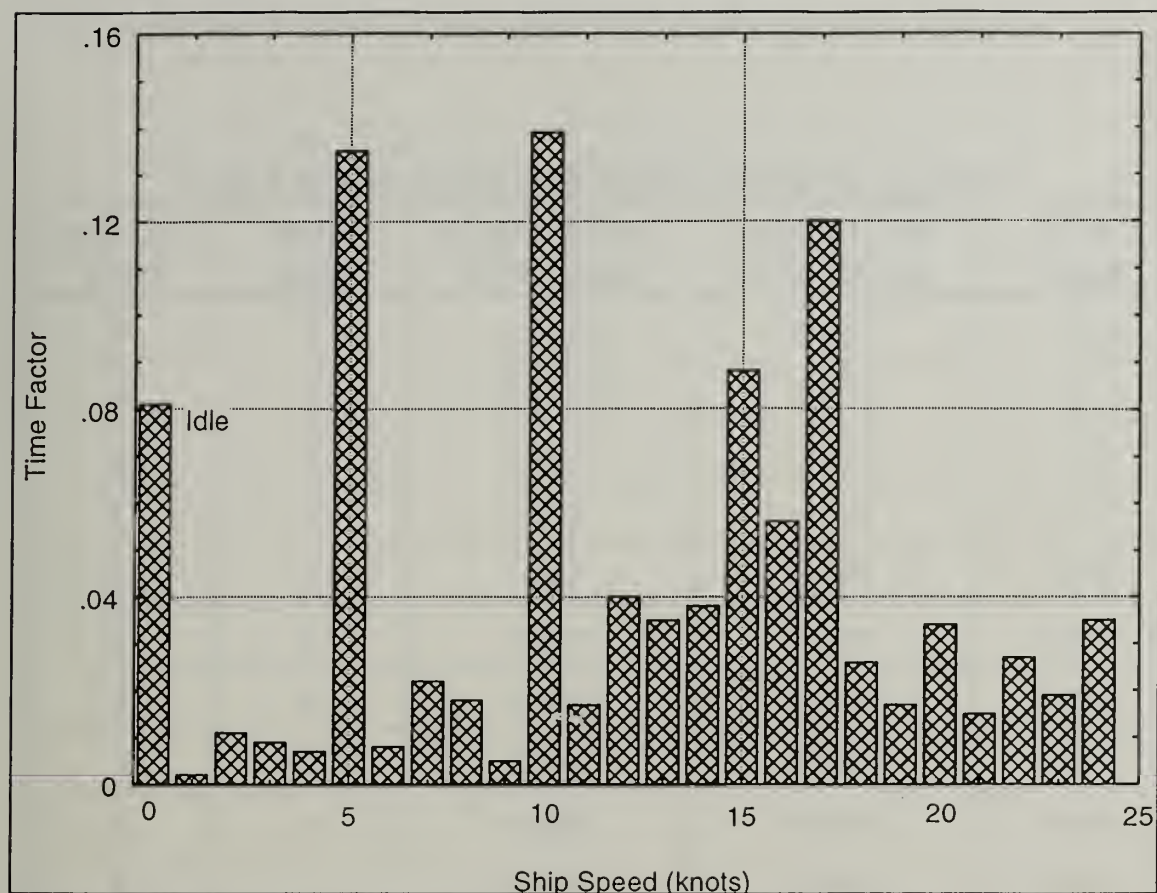


Figure 13: LSD 41 Class Composite Speed Operating Profile

The ship speeds and composite time factors given in Figure 13 should be representative of most naval diesel powered ships while they operate in areas close to shore. The speed profile given in Figure 13 shows that the LSD 41 Class operates primarily in the higher speed ranges centered around 17 knots. Time factor spikes exist at 0, 5 and 10 knots. The value for 0 knots is comprised of cold and warm idle. Cold idle has a time factor of 0.014 and warm idle 0.067, making warm idle greater than cold idle by a factor of five.

The method illustrated by the flowchart of Figure 12 links ship speed to MPE speed and power. Table 2-9 gives this relation for ship speeds below 10

knots and Table 2-10 shows this relation for speeds 10 knots and above.

Table 2-9: Composite MPE Operation Points (0-9 knots)

Engines/ Shaft	Ship Speed	Engine Speed (% of Rated)	Engine Load (% of Rated)	Time Factor
0	0	Cold Idle	0.000	0.014
0	9	Warm Idle	0.026	0.004
2	2	0.387	0.026	0.012
1	2	0.387	0.018	0.001
2	3	0.387	0.018	0.005
2	4	0.387	0.026	0.033
2	5	0.387	0.038	0.033
1	3	0.387	0.037	0.001
2	6	0.387	0.038	0.003
2	7	0.387	0.045	0.005
1	4	0.387	0.052	0.002
2	9	0.387	0.054	0.004
0	9	0.387	0.065	0.003
1	5	0.387	0.065	0.002
1	6	0.387	0.077	0.005
1	7	0.387	0.091	0.017
1	8	0.387	0.108	0.014
1	9	0.387	0.129	0.002

Table 2-10: Composite MPE Operation Points (10-24 knots)

Engines/ Shaft	Ship Speed	Engine Speed (% of Rated)	Engine Load (% of Rated)	Time Factor
2	10	0.398	0.079	0.056
1	10	0.398	0.098	0.083
2	11	0.440	0.098	0.002
2	12	0.440	0.122	0.012
2	13	0.531	0.152	0.010
2	17	0.573	0.189	0.010
1	11	0.440	0.195	0.015
2	10	0.615	0.234	0.031
1	12	0.440	0.243	0.028
2	10	0.658	0.288	0.015
1	13	0.531	0.303	0.028
2	17	0.440	0.352	0.015
1	14	0.573	0.378	0.028
2	10	0.742	0.426	0.041
1	10	0.615	0.098	0.057
2	19	0.735	0.513	0.017
1	16	0.658	0.576	0.041
2	20	0.833	0.612	0.034
1	17	0.712	0.724	0.105
2	21	0.875	0.724	0.015
2	20	0.917	0.851	0.028
1	18	0.735	0.853	0.015
2	23	0.958	0.993	0.019

2	24	1.000	1.000	0.035
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The SSDG operating profile was much simpler to determine than the ship speed profile. In this case, the Engineering Smooth Log and engine operating logs were reviewed. Table 2-11 provides the SSDG composite operating profile summary.

Table 2-11: Composite SSDG Engine Operating Profile Time Factors

Engine Speed (% of Rated)	Engine Load (% of Rated)	Time Factor
1.000	0.000	0.026
1.000	0.192	0.007
1.000	0.400	0.200
1.000	0.500	0.464
1.000	0.600	0.266
1.000	0.808	0.026
1.000	1.000	0.011

Figure 14 describes the SSDG operating profile graphically. This graph clearly indicates that operation of the LSD 41 Class SSDG's is concentrated around the 50 percent load point.

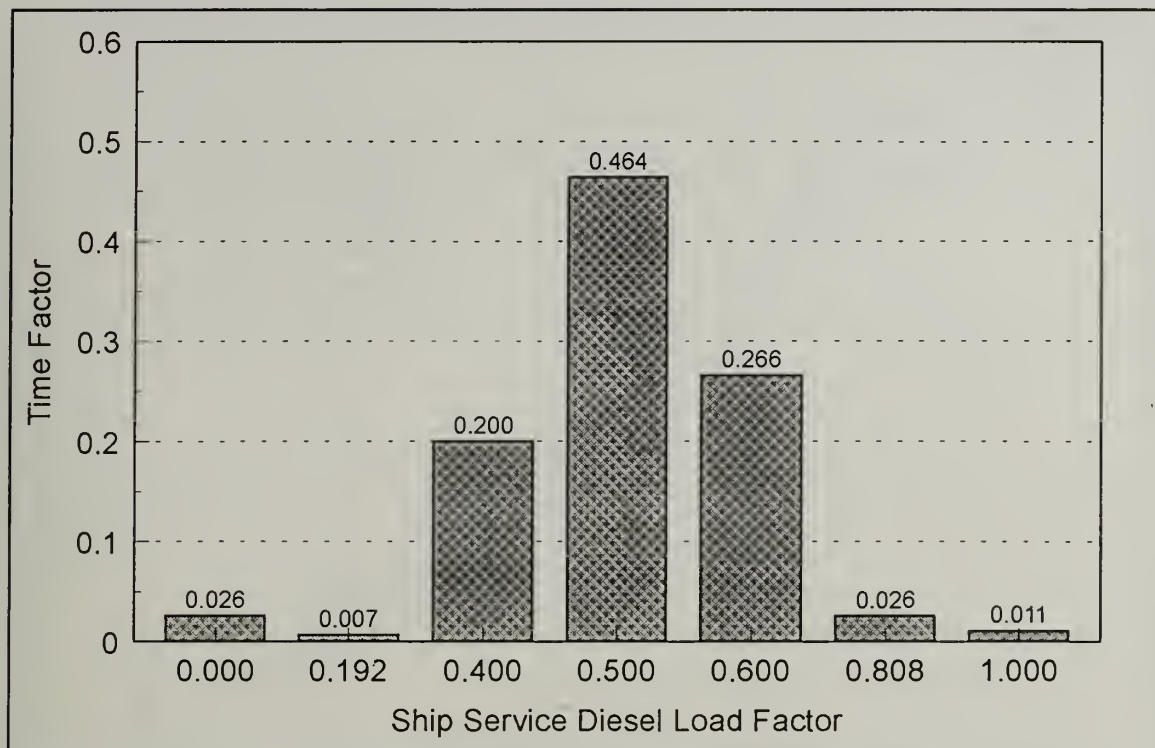


Figure 14: LSD 41 Class Composite SSDG Operating Profile

2.5 Operating Profile Coastal Variation

The ship operating profile provided in Figure 13 is a composite of four ships profiles. Figure 15 illustrates the variation between the four ships. Figure 16 delineates the variation between ships operating on the east and west coasts and compares them to the composite operating profile.

The comparison between ships in Figure 15 shows that each ship is operated in generally the same manner. Trends given by the four curves are of the same shape; they track within a band of 18 percent variation. The greatest variation occurs at speeds above 10 knots. The indicated variation is largely dependent upon the evolutions each ship was engaged in as well as the

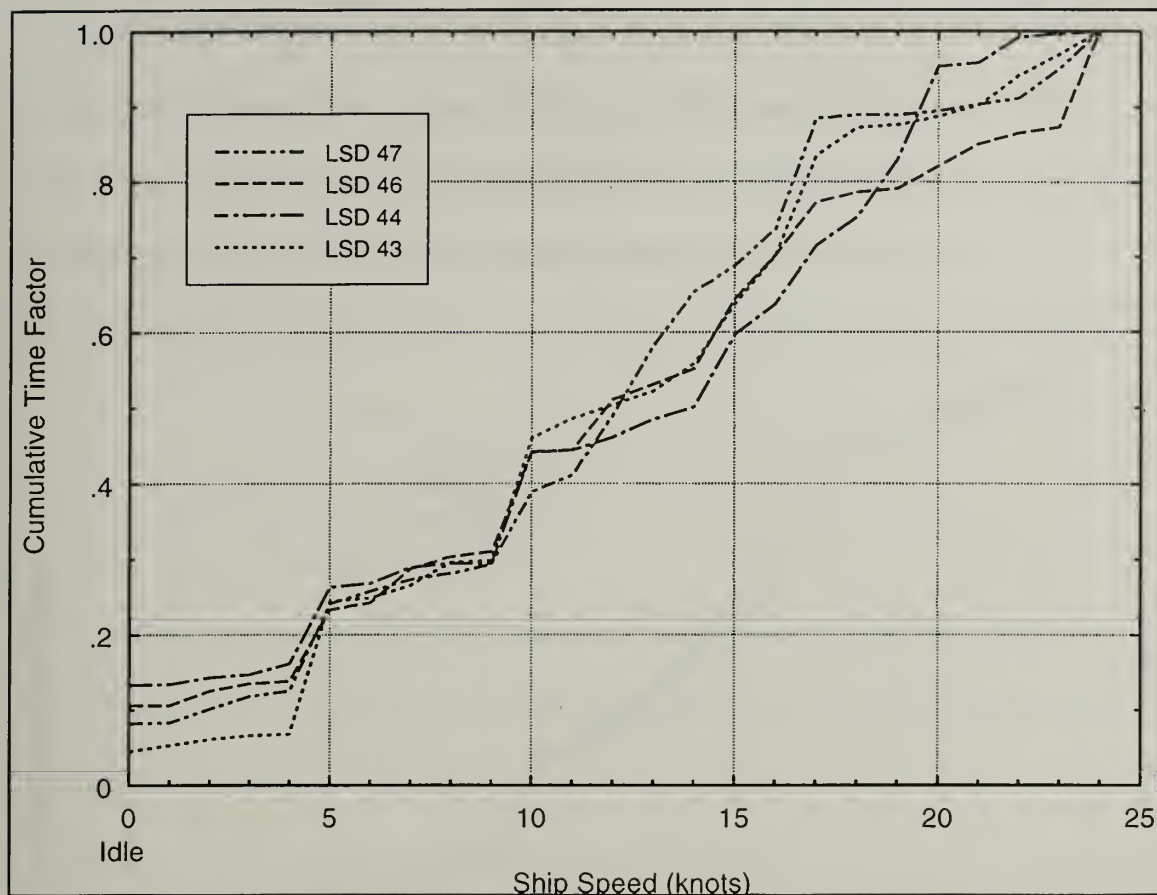


Figure 15: Ship Operating Profile Cumulative Time Factor Comparison

preference of the individual operator.

The comparison shown in Figure 16 is much closer than the comparison of Figure 15. In Figure 16, the widest variation occurred at 17 knots with a span of 15 percent. Except for the region between 16 and 19 knots the three curves tracked very close to one another. The variation below 4 knots was due to differences in time spent at idle. West coast ships spent approximately 7 percent more time at idle than did east coast ships. The greater amount of time spent by west coast ships at idle is primarily due to the layout of the harbor and geometry of the piers. The profile followed by west coast ships takes more time

than east coast ships to reach open water. The use of tugs by west coast ships is also greater due to the greater difficulty in maneuvering close to the nested piers. The composite curve tracked closest to the east coast indicating that the operating profile was most heavily influenced by east coast ships.

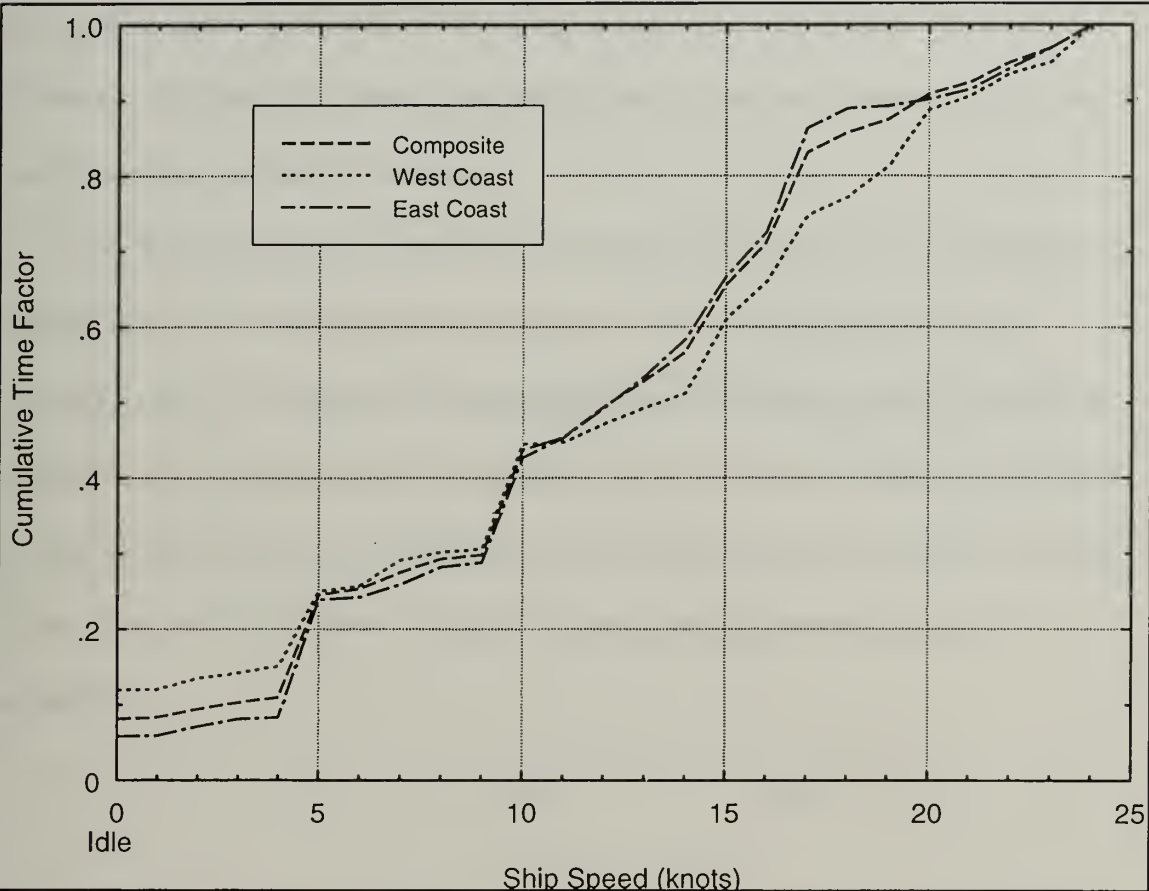


Figure 16: Operating Profile Cumulative Time Factor Comparison by Coast

Chapter 3: NAVAL DIESEL ENGINE DUTY CYCLE DEVELOPMENT

3.1 Naval Main Propulsion Diesel Engine Duty Cycle

A duty cycle must provide an accurate model of the range of speed and power points at which an engine is operated, and also be concise and easy to use. A duty cycle consisting of five to ten modes is preferable to one using ten to fifteen, provided it accurately reflects engine operation. However, accuracy should not be sacrificed for brevity.

To date, most duty cycles have been developed for generic application to a wide variety of land based power systems. These systems are on-road vehicles, non-road vehicles and heavy equipment, railroads, power generating facilities and portable industrial equipment. For land based propulsion systems a direct relation between output required and vehicle weight and friction usually exists. The relation to overcome static friction (initiate motion) is given in equation 10.

$$F = \mu L \quad (10)$$

Where the friction force, F , is proportional to the normal force, L , and μ is the coefficient of static friction. Once the vehicle begins to move, its motion is governed by the dynamic relation given as equation 11.

$$F_R = \frac{v_s}{v_r} F_K \quad (11)$$

Where total rolling friction, F_R , is proportional to the ratio of slip velocity, v_s , to

rolling velocity, v_r , and F_K the kinetic coefficient of sliding friction. The ratio of slip velocity to rolling velocity describes slippage to rolling amount occurring at the interface between two bodies in relative motion. Equations 10 and 11 apply to each component in the drive train from piston rings/cylinder walls to tires and road surface. Since equations 10 and 11 describe linear motion, the rule of superposition may be used to sum their cumulative effect. Equation 3 defines mechanical efficiency and is closely related to the additive effects of equation 10 and 11. Air resistance contributes a greater proportion of the total resistance to land vehicle motion. This is due to smaller overall vehicle weights.

To achieve a given speed, larger vehicles will have larger propulsion engines. For power generation systems, power output is related to generator size. Size dictates torque and power requirements of the prime mover. For a given application, the prudent designer selects an engine size optimized for both fuel efficiency and power output. For example, locomotive engines are designed to pull a specific number and weight of railroad cars at an optimum rail speed. Regardless of the manufacturer or size of the land vehicle, the percent plant output for a given speed is fairly constant. Automobiles and trucks require similar relative engine power output to travel at normal highway speeds. Semi-tractor-trailer on-road trucks use an equivalent speed/power relation throughout design speed ranges. The wide variety of land based equipment and engine combinations is readily modeled by generic duty cycles. For example, in most applications the thirteen duty cycles of ISO 8178-4 effectively cover the

spectrum of land based reciprocating internal combustion engine operation.

Section 2.2 describes the forces resisting ships motion. Underwater hull form shape and wetted surface area determine the powering requirement for a given speed. The simple relations of equations 10 and 11 do not describe ship resistance; therefore, the hull specific speed power relation, typified by Figure 9, must be used. Commercial ship engines are designed to provide optimum fuel economy at some cruising speed. Engines are sized according to ships full load weight. For an established cruising speed, the fraction of rated engine RPM and engine power are relatively constant. The theory behind ISO 8178-4 duty cycles E1, E2 and E3 reflects operation at a few engine speed/power combinations. For most of their operational life these ships cruise at between 15 and 20 knots.

Naval ship engines are sized for performance rather than efficiency. The ship hull is established and propulsion plant sized to provide some design sustained speed in excess of the endurance (cruise) speed. For example, the operating profile of Figure 13 shows that the LSD Class has a top speed of 24 knots. However, it operates most frequently at 17 knots. This apparent overcapacity in propulsion plant power results in an extremely wide range of engine operating combinations. The majority of naval ship hulls are displacement type but of many different shapes. Each has a distinct speed power relation. The diversity of diesel engine sizes and types, coupled with the wide variety of hull form designs, complicates the use of generic speed power simplifications.

A study comparing engine horsepower to vehicle weight shows that consistency exists in the form of the relation between vessels of different employment and land vehicles of different sizes. Figure 17 depicts several curves of horsepower (HP) normalized to vehicle weight or vessel displacement (Δ) plotted against weight/displacement. The curves have the same general shape, given by the relation of equation 12.

$$\frac{HP}{\Delta} = \alpha \times \Delta^{-\beta} \quad (12)$$

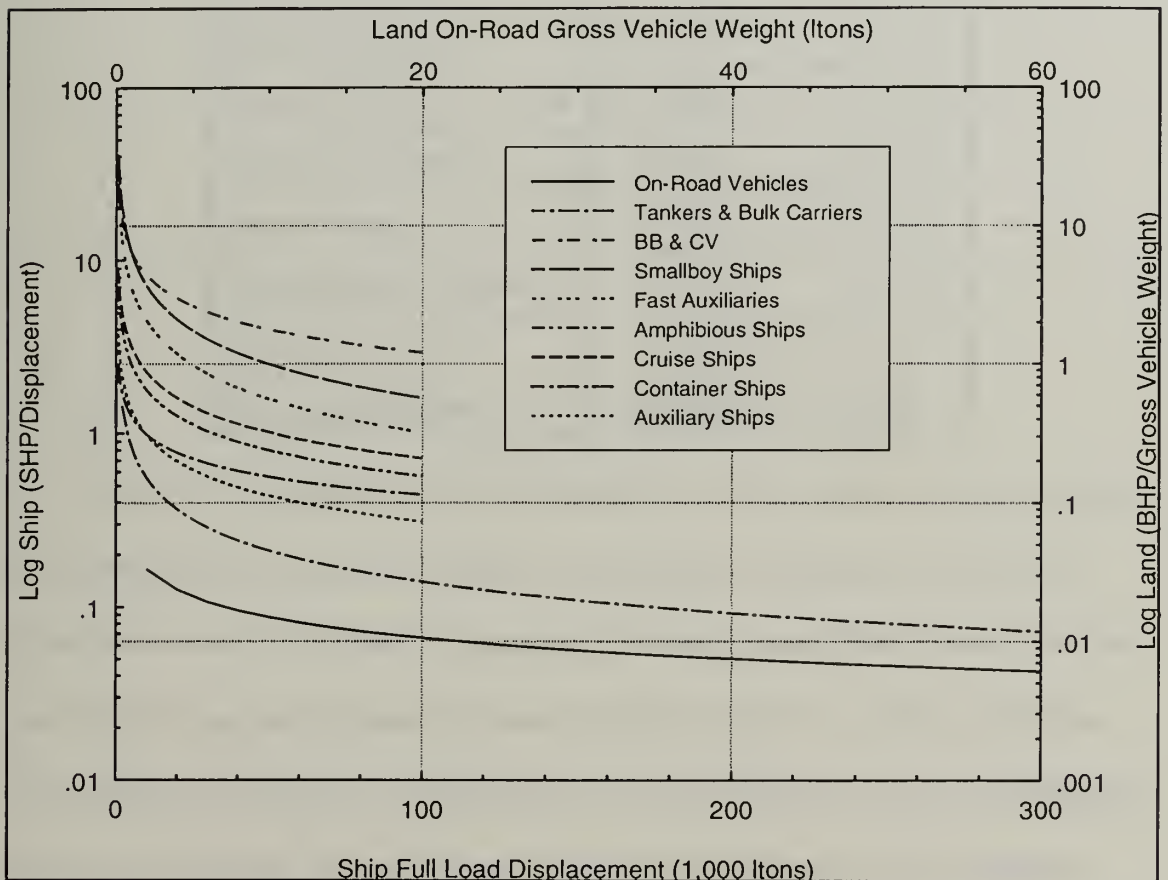


Figure 17: Power Normalized to Weight versus Weight

Rearrangement of equation 12 gives the relation between horsepower

and vehicle weight given by equation 13.

$$HP = \alpha \times \Delta^{(1-\beta)} \quad (13)$$

The curve fit constants α and β describe vessel/vehicle shape and resistance parameters. Table 3-1 gives the values α and β for the curves of Figure 17.

Table 3-1: Horsepower to Displacement Coefficients

Figure 17 Curve	α	β
BB & CV	23.2	0.45
Smallboy Ships	31.9	0.60
Fast Auxiliaries	20.1	0.65
Auxiliary Ships	3.095	0.50
Amphibious Ships	5.647	0.50
Cruise Ships	7.164	0.50
Tankers/Bulk Carriers	2.77	0.60
Container Ships	2.21	0.35
On-Road Vehicles	0.0473	0.50

BB & CV type ships are battleships and aircraft carriers, smallboy ships are warships cruiser size and smaller, fast auxiliary ships have a maximum speed in excess of 25 knots. By grouping the ships evaluated by ship type the perturbation caused by speed differences were avoided. α tends to describe ship speed as a function of displacement. Large fast ships, such as battleships and aircraft carriers, have a higher α than large slow ships such as tankers. This trend is continued into the on-road regime with α on-road several orders of magnitude less than marine vessels. β is related to the shape of the individual

curve, expressing the range, or scatter, of ships evaluated within a ship classification. The higher value of β indicates closer correlation between individuals within a category. The limit of β is likely much less than unity.

Figure 17 shows the wide variability in displacement and ship power requirements. Some correlation does exist between on-road land based and marine vehicles. However, four orders of magnitude separate the nine vehicle types studied. The simplistic analysis represented by equations 12 and 13 are inadequate to accurately predict engine power requirements for each application. Each hull design has a unique resistance relationship resulting in a myriad of diesel engine options. For these reasons, a simple four or five mode duty cycle is not appropriate to describe naval ship engine operation. Rather, the operating (speed) profile must be determined then engine speed and power calculated based on appropriate relationships. The process is essentially the same given in Figure 12. Figure 18 provides a flow chart for determining the individual ship type propulsion plant duty cycle.

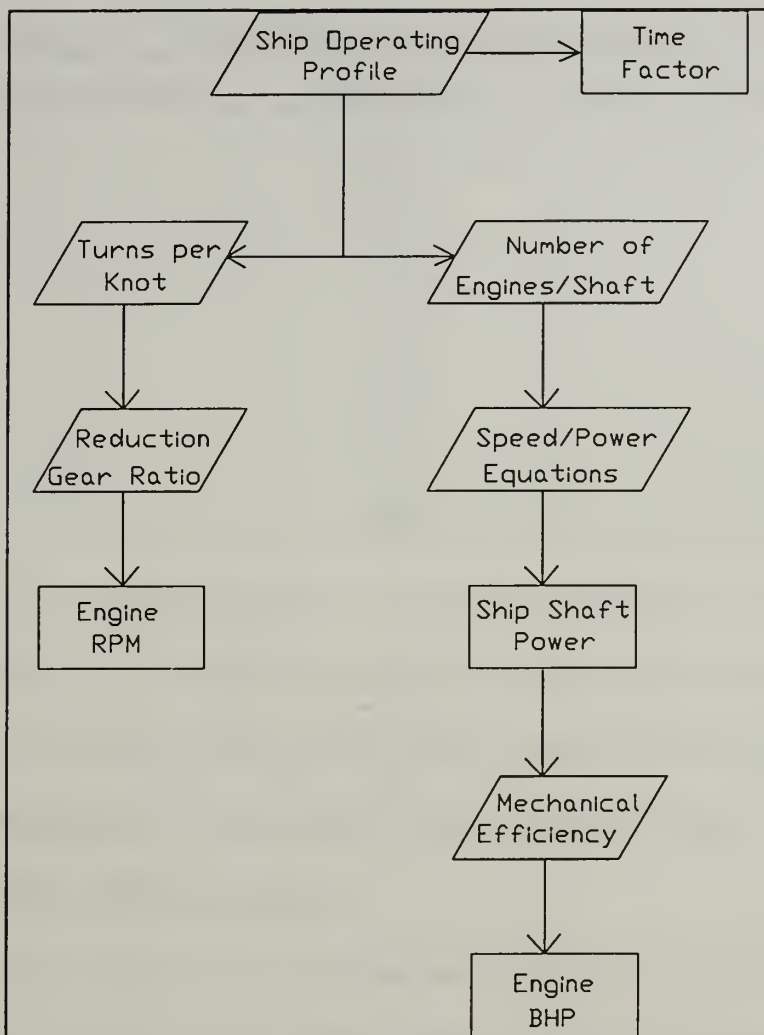


Figure 18: Naval Ship Duty Cycle Determination

The entering arguments of Figure 18 are the standard composite operating profile and ship specific propulsion train and powering information. The composite operating profile of Figure 13 has been reduced from 25 to seven speed points. Speed points and associated time factors are given in Table 3-2. Ranges covered by each speed point were grouped by engine speed and power around each major speed spike indicated in Figure 13.

Table 3-2: Consolidated Naval Ship Operating Profile

Ship Speed (knots)	Time Factor	Speed Range (knots)
0	0.083	Idle - 1
5	0.160	2 - 7
10	0.208	8 - 12
15	0.160	13 - 15
18	0.200	16 - 18
20	0.093	19 - 22
24	0.054	23 - 24

By using the method of Figure 18 a naval ship specific duty cycle may be readily developed. As some ships may have multiple engines clutched to each shaft, care must be taken to ensure each engine speed/power combination is adequately represented for all machinery lineups normally used.

3.2 LSD 41 Class MPE Duty Cycle

The LSD 41 Class may be operated with either one or two engines per shaft. Both conditions must be included in the resulting duty cycle. The LSD 41 MPE Duty Cycle, as developed from the method given in Figure 18, is given in Table 3-3.

Table 3-3: LSD 41 Class MPE Duty Cycle

Mode	Ship Speed	Engines/ Shaft	Engine Speed (% of Rated)	Engine Power (% of Rated)	Time Factor
1	0	0	Idle	0.000	0.083
2	5	1	0.387	0.068	0.064
3	5	2	0.387	0.032	0.128
4	10	1	0.398	0.158	0.077
5	10	2	0.398	0.078	0.141
6	15	1	0.615	0.468	0.051
7	15	2	0.615	0.234	0.109
8	17	1	0.700	0.700	0.040
9	17	2	0.700	0.352	0.160
10	20	2	0.833	0.612	0.093
11	24	2	1.000	1.000	0.054

3.3 T-AO 187 Class MPE Duty Cycle

To demonstrate the use of Figure 18 in developing duty cycles for other naval ships, the T-AO 187 Class was selected. The T-AO 187 Class of fleet oilers is equipped with two shafts. Each shaft is driven by a single Colt-Pielstick PC4-2 diesel engine. The combined 32,540 bhp propels the two shafts and powers the 39,400 ton ship to a maximum speed of just over 19 knots.

Resistance and powering information was determined by using the *MONO-LA* variant of the computer program *Advanced Surface Ship Evaluation Tool* (ASSET). The ship is RPM limited since it reaches rated RPM before reaching rated power. Curve fitting the speed/power data produced the required frictional and residuary resistance speed power relationships. Table 3-4, and equations

14 and 15 give the data required to enter Figure 18 to compute T-AO 187 Class MPE Duty Cycle.

Table 3-4: T-AO 187 Propulsion Plant Data

Engine RPM	
Turns per knot	4.86
Reduction Gear Ratio	4.24
Engine BHP	
Mechanical Efficiency	0.975

Frictional resistance regime is governed by equation 14 and is valid from 0 to 12 knots.

$$SHP=65 \times S^2 - 267 \times S + 155 \quad (14)$$

Residuary resistance regime is represented by equation 15 and is valid from 12 to 20 knots.

$$SHP=22 \times S^3 - 756 \times S^2 + 10300 \times S - 47000 \quad (15)$$

S in equations 14 and 15 is ship speed in knots.

Table 3-5 illustrates the T-AO 187 Class MPE Duty Cycle using the method of Figure 18 and the operating profile developed in Chapter 2. The T-AO 187 Class operating profile has been approximated by the LSD 41 Class profile for illustrative purposes. Use of the LSD 41 Class profile may not be a reasonable assumption, a separate profile should be developed.

Table 3-5: T-AO 187 Class MPE Duty Cycle

Mode	Ship Speed	Engine Speed (% of Rated)	Engine Power (% of Rated)	Time Factor
1	0	Idle	0.000	0.083
2	5	0.500	0.014	0.192
3	10	0.500	0.0126	0.218
4	15	0.774	0.367	0.160
5	17	0.876	0.558	0.293
6	19	1.000	0.917	0.054

3.4 LSD 41 Class SSDG Duty Cycle

Typical electric plant loads for LSD 41 Class ships vary from 1,500 to 1,800 kW delivered at between 1,100 and 1,500 amps. Since rated generator size is 1,300 kW, SSDG's of the LSD 41 Class are most often operated at approximately 50 percent load. Data given in Table 2-11 suggests a reasonable six-mode, constant speed duty cycle. Table 3-6 provides the LSD 41 Class SSDG Duty Cycle.

Table 3-6: LSD 41 Class Ship Service Diesel Engine Duty Cycle

Mode	Engine Speed	Engine Load	Time Factor
1	1.000	0.000	0.033
2	1.000	0.400	0.200
3	1.000	0.500	0.464
4	1.000	0.600	0.266
5	1.000	0.800	0.026
6	1.000	1.000	0.011

Variability of engine/generator set combinations and ship electrical power requirements impedes development of a SSDG operating profile appropriate for all ship types. Most naval SSDG's are operated at much higher loads than typically found on the LSD 41 Class. ISO 8178-4 constant speed duty cycles D1 or D2, illustrated in Table 1-13, may be appropriate for naval application. Atypical operation of LSD 41 Class SSDG's requires the more detailed duty cycle delineated in Table 3-5. Realistically, SSDG data is available onboard each U.S. Naval ship to easily calculate time factors for adjusting the duty cycle of Table 3-5, ISO 8178-4 D1 or D2.

Chapter 4: Duty Cycle Comparison

Diesel engine duty cycle comparisons were performed to validate methodology used in preparing naval ship duty cycles, and compare them to industry accepted standards.

4.1 Comparison Methodology

The MPE comparisons were performed using emission contour maps provided in *The Motor Ship* article "Designers Anticipate Engine Emission Controls", of August 1992. Emission contour maps plot emissions as a function of engine speed and power. Three dimensional information is displayed as a contour map in two dimensions. Contour maps provided in *The Motor Ship* were based on the Colt-Pielstick PC4-2B engine with specific emission levels given in g/kW-hr. Graphs were normalized to rated power and RPM to give maximum speed and power values of unity. Emission curves were converted from metric to english units of g/bhp-hr. Curves were then reproduced in the computer program *Easy Plot* to facilitate comparison. Figures 19 to 22 illustrate the emission contour maps used. Engine power was normalized to Power Fraction using Equation 16 and engine RPM was reduced to RPM Factor by Equation 17.

$$Power_{Fraction} = \frac{Power_{Point}}{Power_{Rated}} \quad (16)$$

$$RPM_{Factor} = \frac{RPM_{Point} - RPM_{Idle}}{RPM_{Rated} - RPM_{Idle}} \quad (17)$$

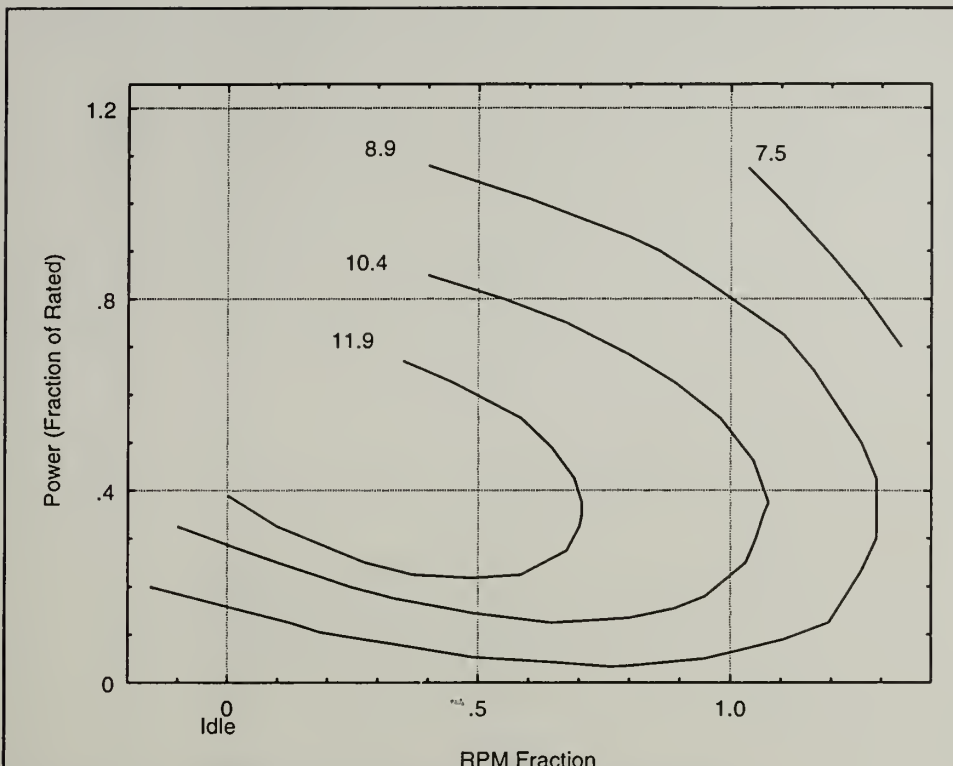


Figure 19: NO_x Emission Contour Map (g/bhp-hr)

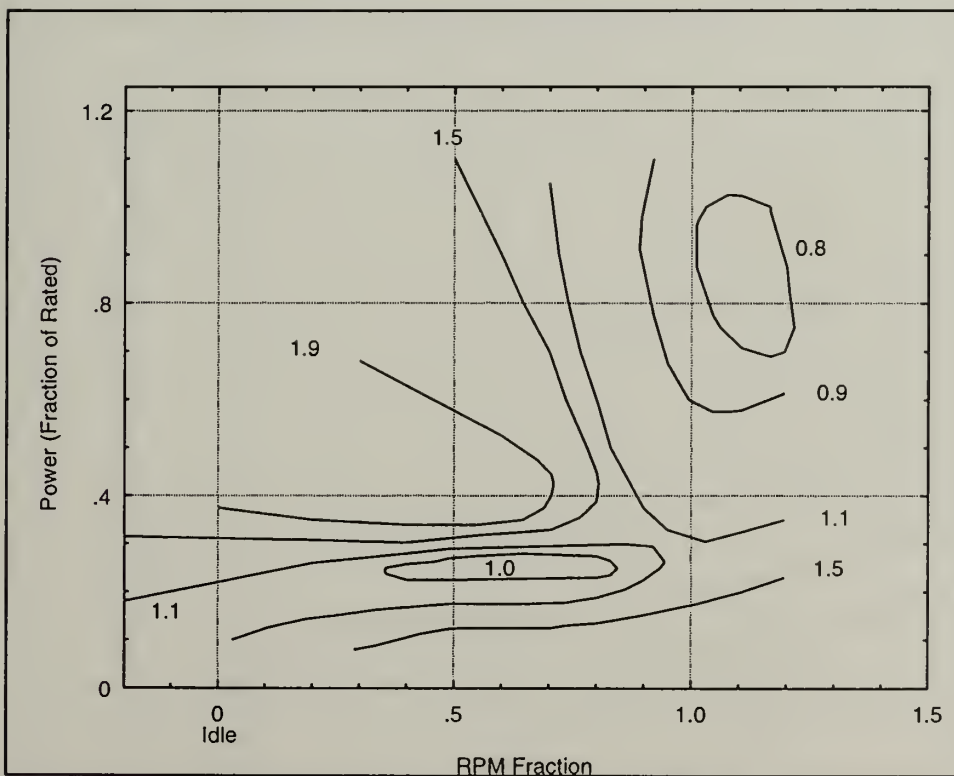


Figure 20: CO Emission Contour Map (g/bhp-hr)

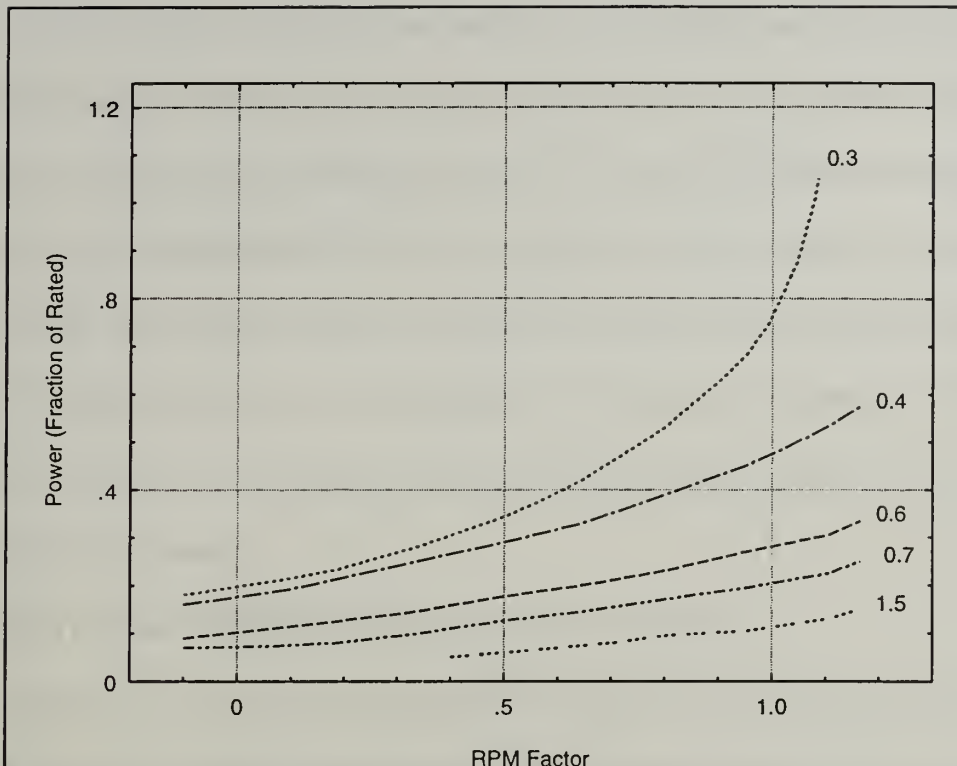


Figure 21: HC Emission Contour Map (g/bhp-hr)

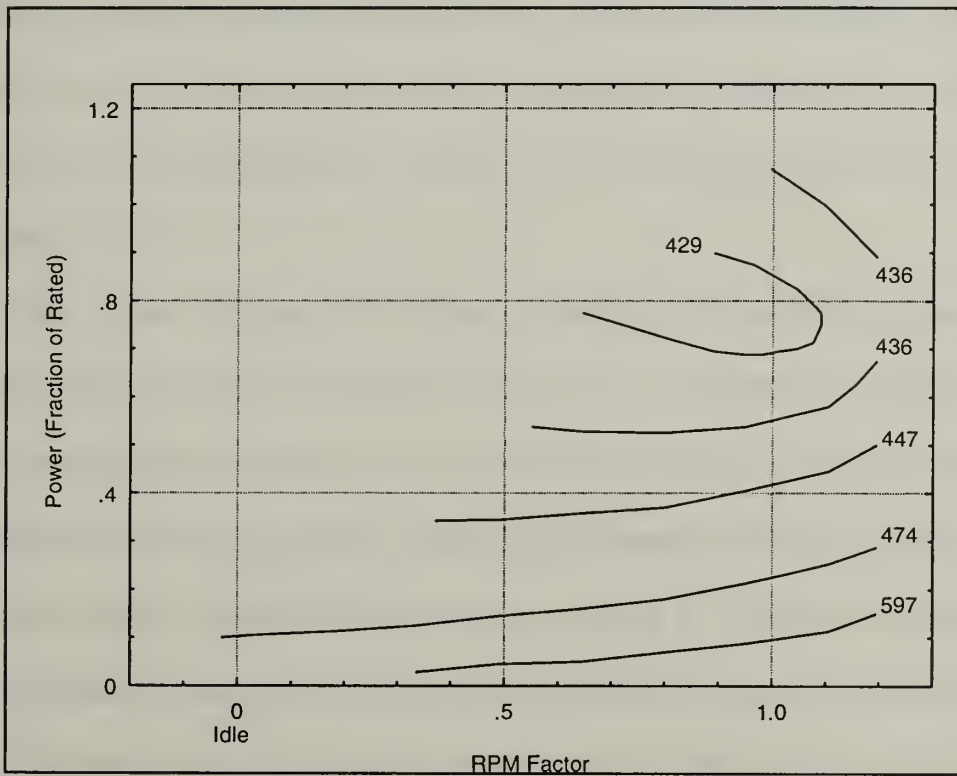


Figure 22: CO₂ Emission Contour Map (g/bhp-hr)

Engine emission analysis was performed by plotting each duty cycle on the four emission contour maps. Emission values for the idle condition were based on the work of V. W. Wong in his work "Transient Emissions Breakdown Analysis", *Cummins Report 0749-79007* of 23 May 1979. Average idle emission for nine engines was calculated as a percent of emission level observed at power. For NO_x this value was 2.6 percent of the maximum observed, or 0.31 g/bhp-hr in Figure 19. Appendix C contains the data used to generate the emission contour maps.

4.2 LSD 41 Class MPE Duty Cycle Emission Prediction

Propeller curve plots of single and twin engines per shaft, from the data of Table 2-9 and 2-10, were superimposed on the emission contour maps. Figures 23 to 26 provide these superimposed graphs. Brake specific emission levels were then read from the curves by linear interpolation. Values given describe engine emissions as a function of ship speed. Plots of these curves are shown in Figures 27 to 30.

The curves of Figure 27 to 30 are consistent with data found in the literature. NO_x production, illustrated in Figure 27, is maximized at highest cylinder temperatures. Maximum NO_x production occurs at maximum brake mean effective pressure (bmep), which is approximately 85 percent rated power and engine speed. Maximum bmep occurs very near 17 knots for the engine data illustrated in these curves. Table 2-8 shows that 17 knots is the second highest frequency of occurrence in the composite operating profile. This is not

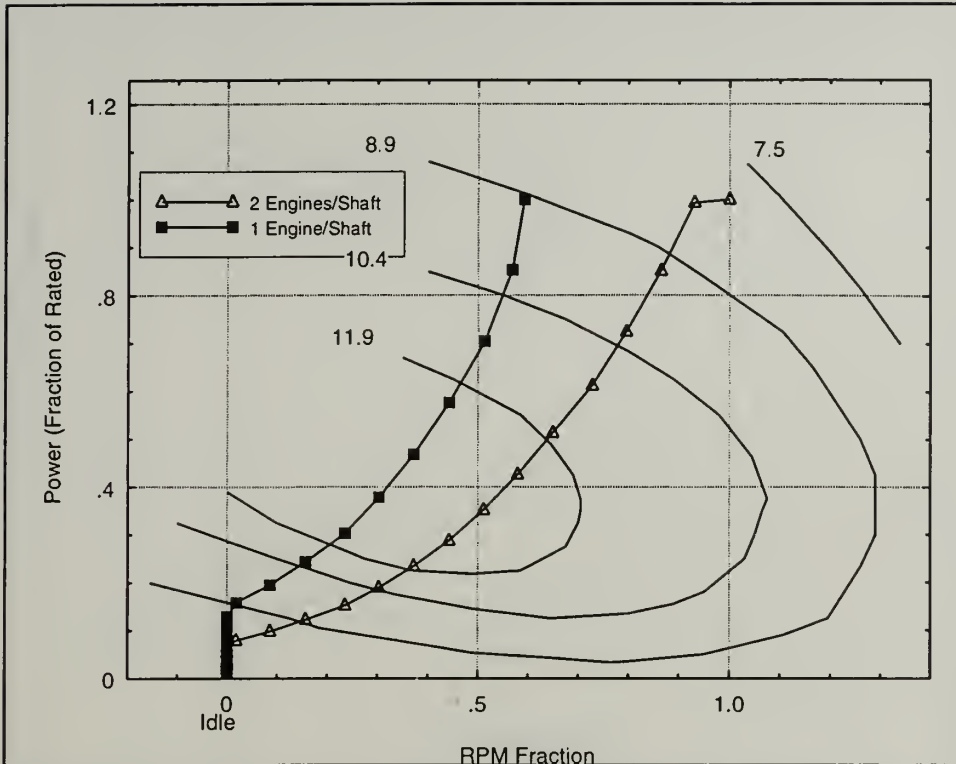


Figure 23: LSD 41 MPE NO_x Emission Contour Map (g/bhp-hr)

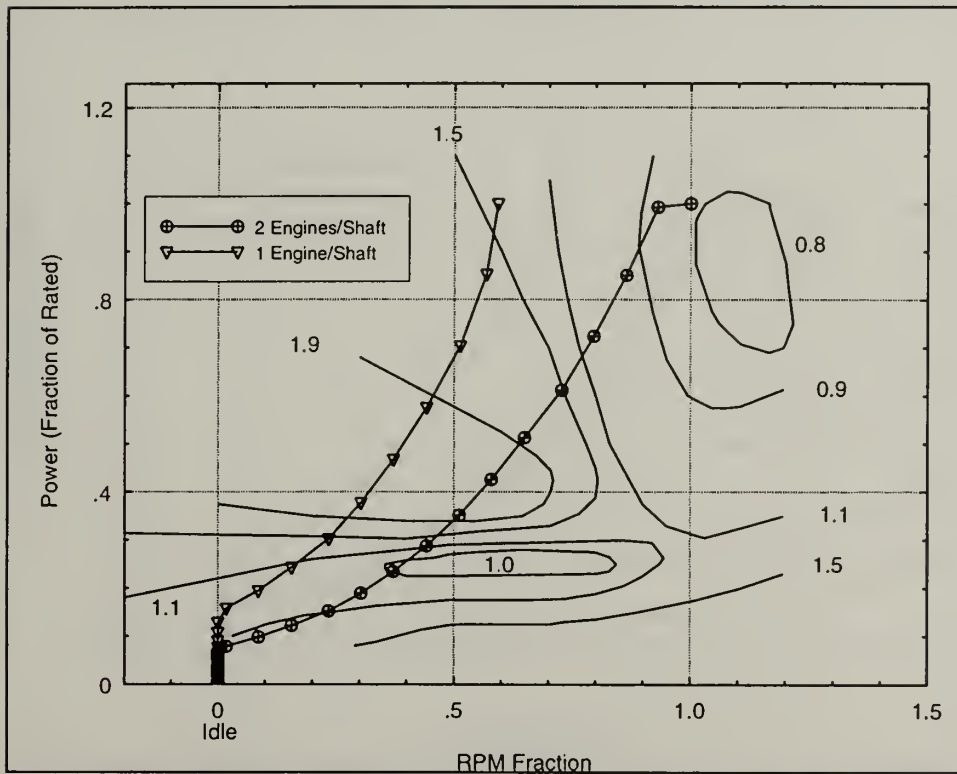


Figure 24: LSD 41 MPE CO Emission Contour Map (g/bhp-hr)

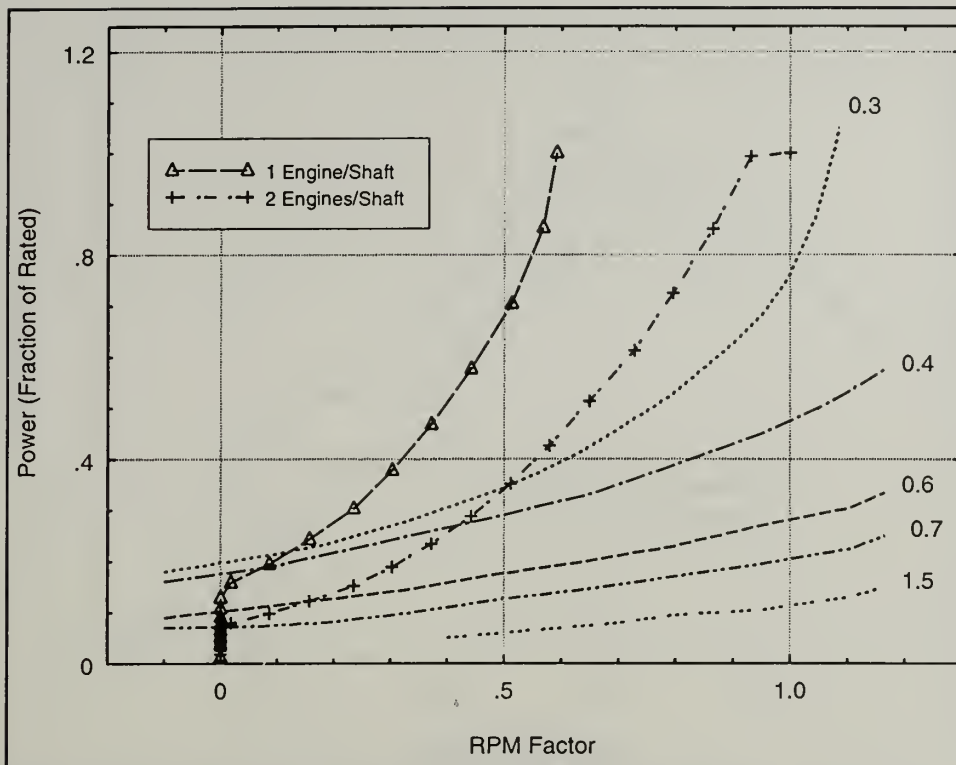


Figure 25: LSD 41 MPE HC Emission Contour Map (g/bhp-hr)

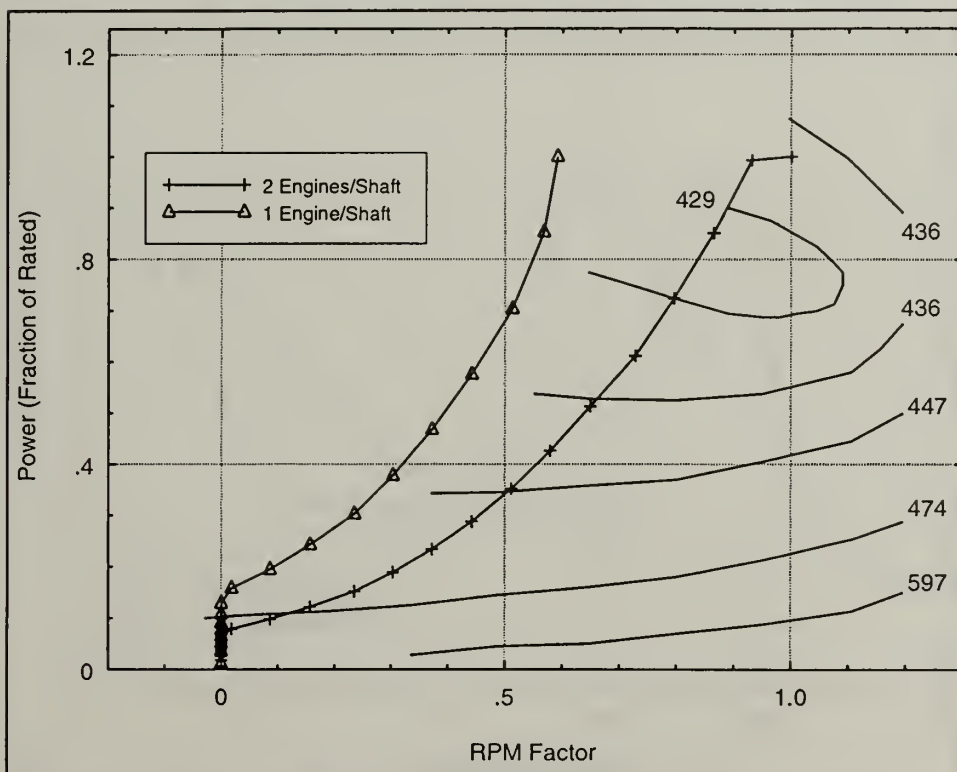


Figure 26: LSD 41 MPE CO₂ Emission Contour Map (g/bhp-hr)

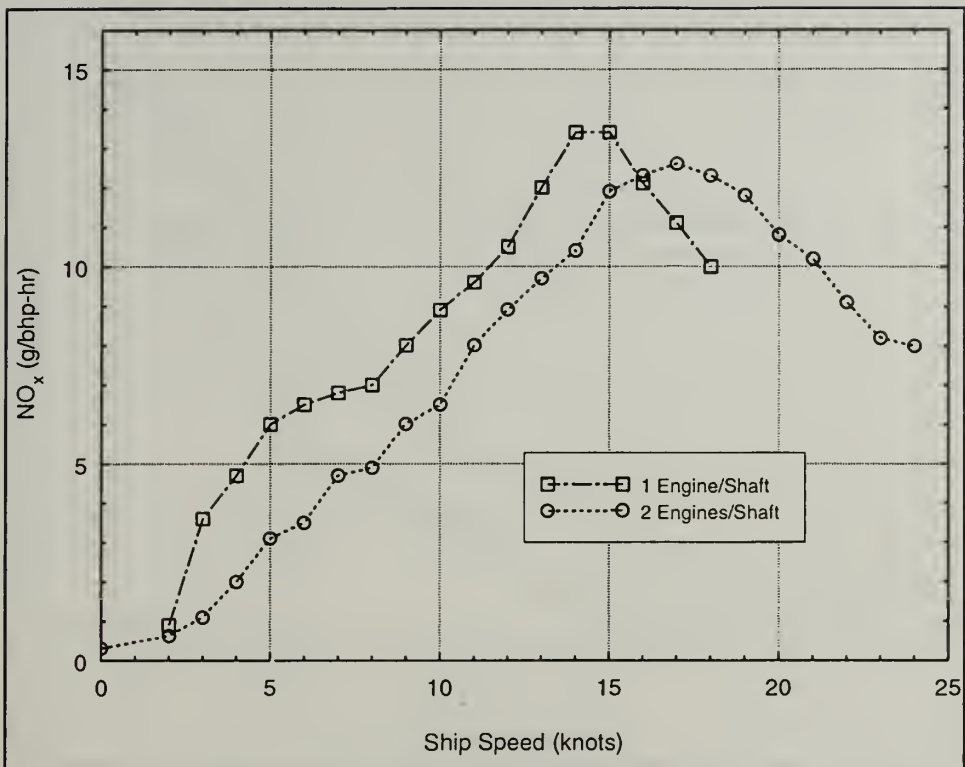


Figure 27: LSD 41 Class Speed vs. NO_x Emissions

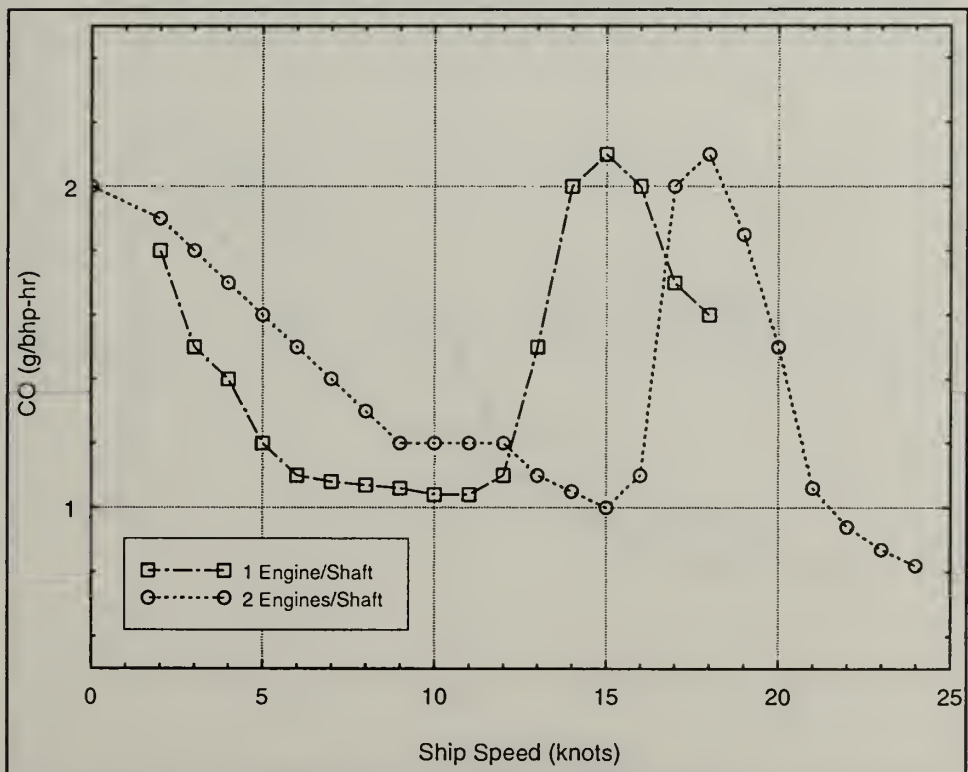


Figure 28: LSD 41 Class Speed vs. CO Emissions

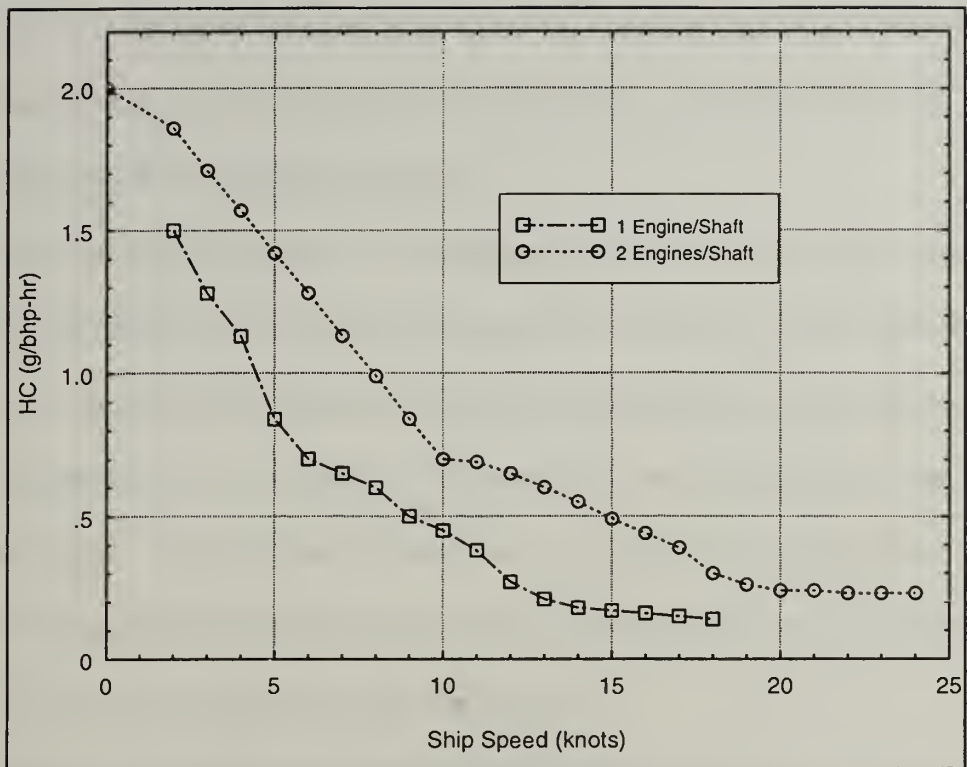


Figure 29: LSD 41 Class Speed vs. HC Emissions

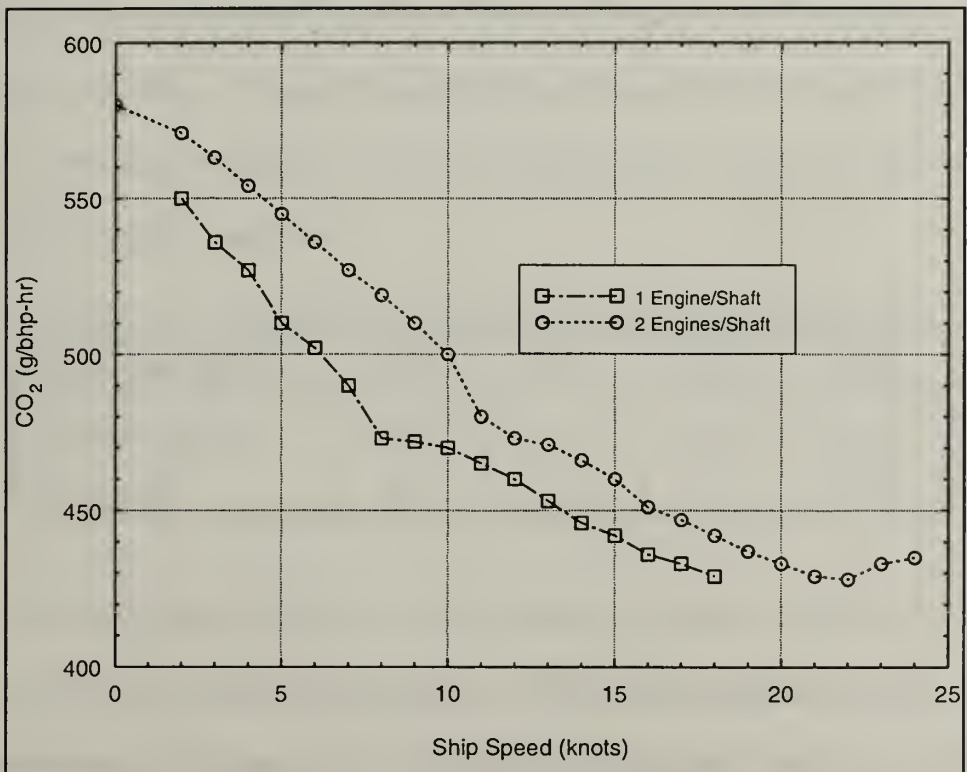


Figure 30: LSD 41 Class Speed vs. CO₂ Emissions

coincidence. 17 knots is the design endurance speed for most U.S. Naval ships. Therefore, by the curve of Figure 27, maximum NO_x production occurs at or near ship speeds used with highest frequency.

The curves of Figures 27 to 30 show the effect of reduced engine output on specific emissions. The plots of one and two engines per shaft indicate power required for specific speed. Figure 27 shows that NO_x levels decrease for lower engine loads. For example, at 15 knots the one engine/shaft curve indicates higher NO_x production than the two engines/shaft configuration. However, two engines/shaft increases both fuel consumption and the production of CO, HC and CO₂ emissions (Figures 28 to 30).

LSD 41 Class MPE Duty Cycle modes listed in Table 3-3 were next superimposed on the emission contour maps and engine specific brake emissions calculated. These emission contour maps appear in Appendix C. Table 4-1 provides the resulting LSD 41 Class propeller curve and LSD 41 Class Duty Cycle emission predictions.

Table 4-1: LSD 41 Class Emission Predictions (g/bhp-hr)

Prediction Method	NO _x	CO	HC	CO ₂
Propeller Curve	8.5	1.5	0.6	475
Duty Cycle	8.3	1.5	0.7	483

Data presented in Table 4-1 shows strong correlation between the propeller curve and duty cycle predictions. Differences between emission values are of the order two percent and deemed negligible. Section 4.3 provides

evaluated and the T-AO 187 Class comparison. The *Lotus 123W* spreadsheet used to calculate duty cycle emissions predictions is also given in Appendix C. Table 4-2 provides the MPE duty cycle comparison. Figures 32 to 36 illustrate the comparison graphically. Included in Table 4-2 is the Japanese NO_x prediction given by the curve of Figure 3. Values for NO_x predicted by the Japanese method are much greater than those predicted by the emission contour map method. However, excellent correlation exists between

Table 4-2: MPE Duty Cycle Emission Prediction Summary (g/bhp-hr)

Method	NO _x	J. NO _x	CO	HC	CO ₂
LSD Class Propeller Curve	8.5	15.9	1.5	0.6	475
LSD Class 11-Mode Duty Cycle	8.3	15.9	1.5	0.7	483
ISO 8178-4 E3 Duty Cycle	9.9	14.4	1.0	0.3	433
ISO 8178-4 E1 Duty Cycle	6.9	16.3	1.6	1.0	499
ICOMIA 36-88 Duty Cycle	6.9	16.2	1.5	1.0	499
Japanese Heavy-Duty Diesel Cycle	9.9	15.9	1.2	0.4	444
U.S. EPA 13-Mode Duty Cycle	7.3	15.4	1.5	1.0	497
CARB 8-Mode Duty Cycle	9.1	14.6	1.1	0.5	452
U.S.N. Endurance Test	7.7	14.3	1.0	0.4	444

the two LSD Class methods demonstrating the validity of operating profile time factors.

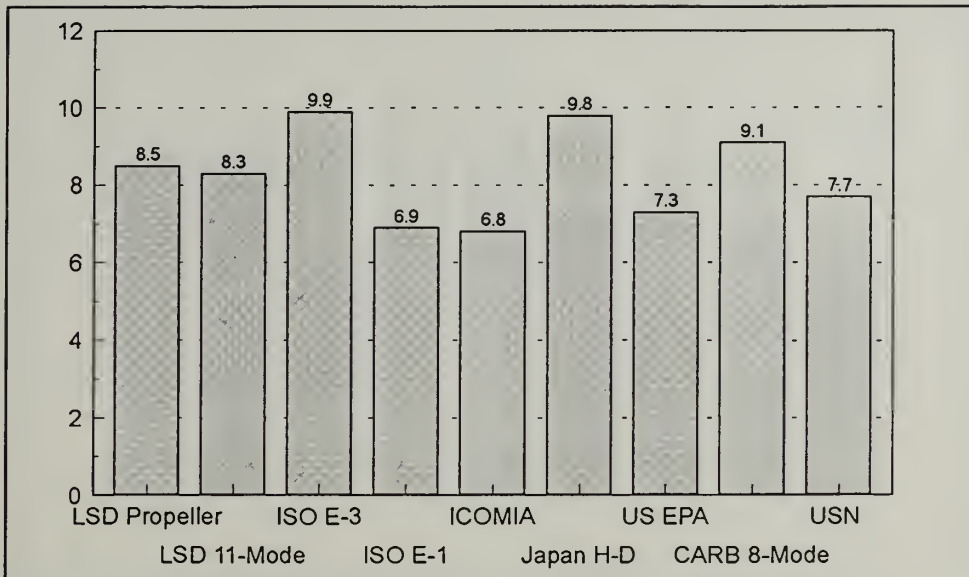


Figure 32: MPE NO_x Prediction Comparison (g/bhp-hr)

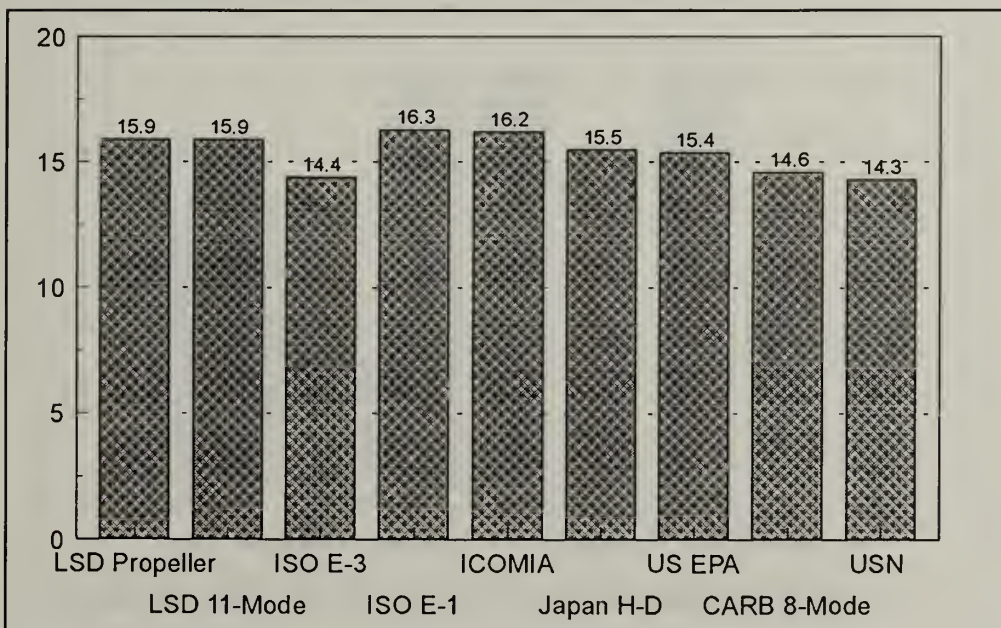


Figure 33: MPE Japanese NO_x Prediction Comparison (g/bhp-hr)

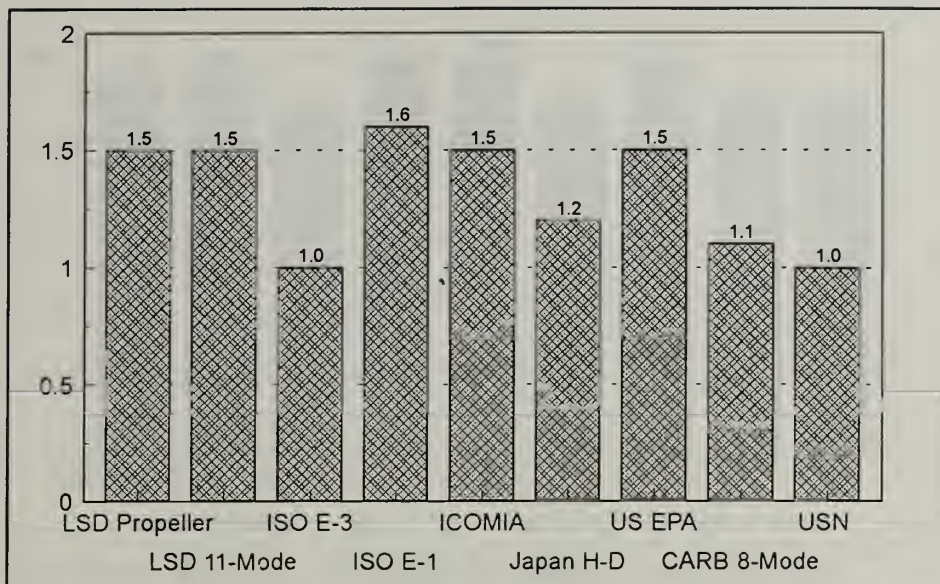


Figure 34: MPE CO Prediction Comparison (g/bhp-hr)

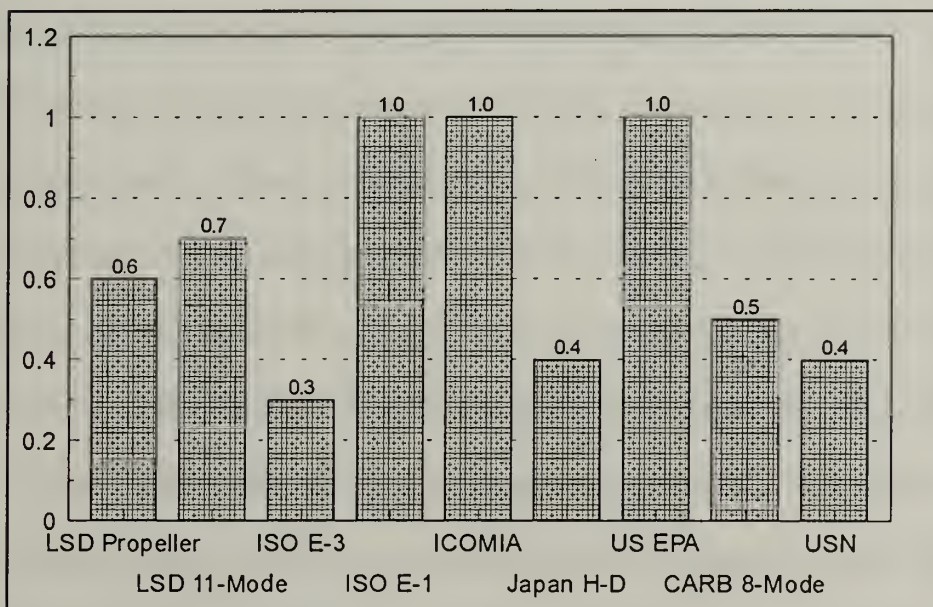


Figure 35: MPE HC Prediction Comparison (g/bhp-hr)

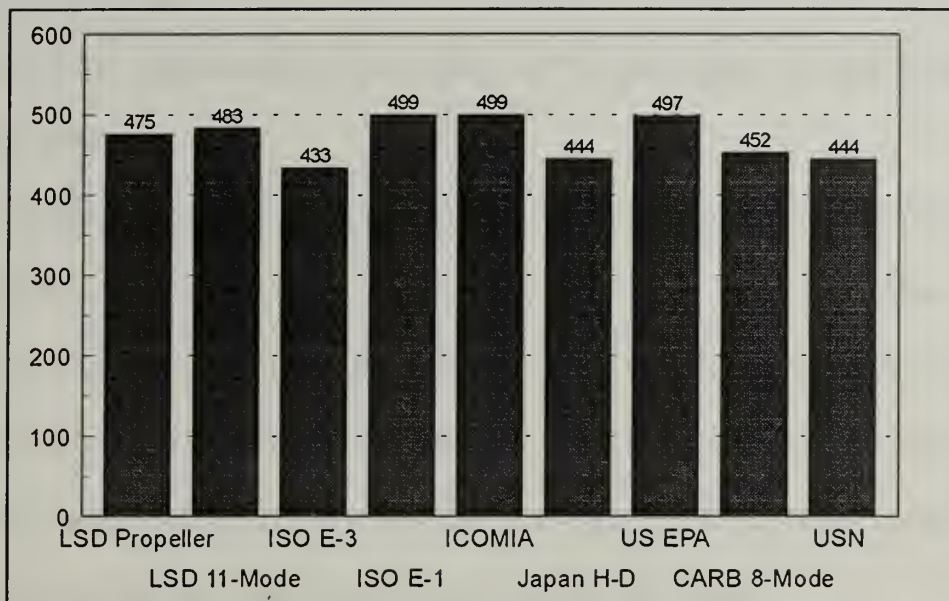


Figure 36: MPE CO₂ Prediction Comparison (g/bhp-hr)

Comparison charts of Figure 32 to 36 show duty cycle variation between emission predictions. In all five figures, the LSD 41 Class 11-Mode Duty Cycle provided the closest comparison to the LSD 41 Class Propeller Curve. The CARB 8-Mode Duty Cycle gives the next best NO_x comparison at 0.6 g/bhp-hr greater than propeller curve prediction (Figure 32). The ICOMIA 36-88 Duty Cycle calculates the second best Japanese NO_x Prediction at 0.3 g/bhp-hr over the propeller curve (Figure 33). CO predictions provided by the LSD 41 Class Propeller Curve, LSD 41 Class 11-Mode Duty Cycle, ICOMIA 36-88 Duty Cycle, and U.S. EPA 13-Mode Duty Cycle are the same (Figure 34). The CARB 8-Mode is second best in predicting HC emissions at 0.1 g/bhp-hr below the propeller curve (Figure 35). For CO₂, the U.S. EPA 13-Mode Duty Cycle follows the LSD 41 Class 11-Mode Duty Cycle at 22 g/bhp-hr over the value of the

propeller curve (figure 36). In short, no single duty cycle offers the consistency of the LSD 41 Class 11-Mode Duty Cycle in predicting LSD 41 Class engine exhaust emissions.

Plotting the propeller curve and calculated duty cycle for the T-AO 187 Class gives similar correlations. Table 4-3 provides the T-AO 187 Class emission predictions. Comparison with the charts of Figures 32 to 36 shows that no other duty cycle approaches the derived T-AO 187 Class 6-Mode Duty Cycle in predicting overall engine emissions for the ship operating profile. Appendix C contains the emission contour plots for the T-AO 187 Class.

Table 4-3: T-AO 187 Class MPE Emission Predictions (g/bhp-hr)

Prediction Method	NO _x	CO	HC	CO ₂
Propeller Curve	7.6	1.4	0.8	482
Duty Cycle	7.7	1.5	0.8	483

4.4 SSDG Duty Cycle Comparison

The SSDG Duty Cycle comparison used emission data generated by Fairbanks Morse for engine 38D880013DGN12 on 30 May 1980. Though the same basic engine as the LSD 41 Class SSDG (38ND8-1/8, 12 cylinder opposed piston diesel engine), the engine tested was run with increased exhaust back pressure and no blower bypass valve. The test was performed on the engine as configured for use on *OHIO* (SSBN 726) Class submarines. Figure 37 provides the emission data for this engine. Constant speed data for no load condition was estimated based on relative comparison with the curves of Figures 19 to 21.

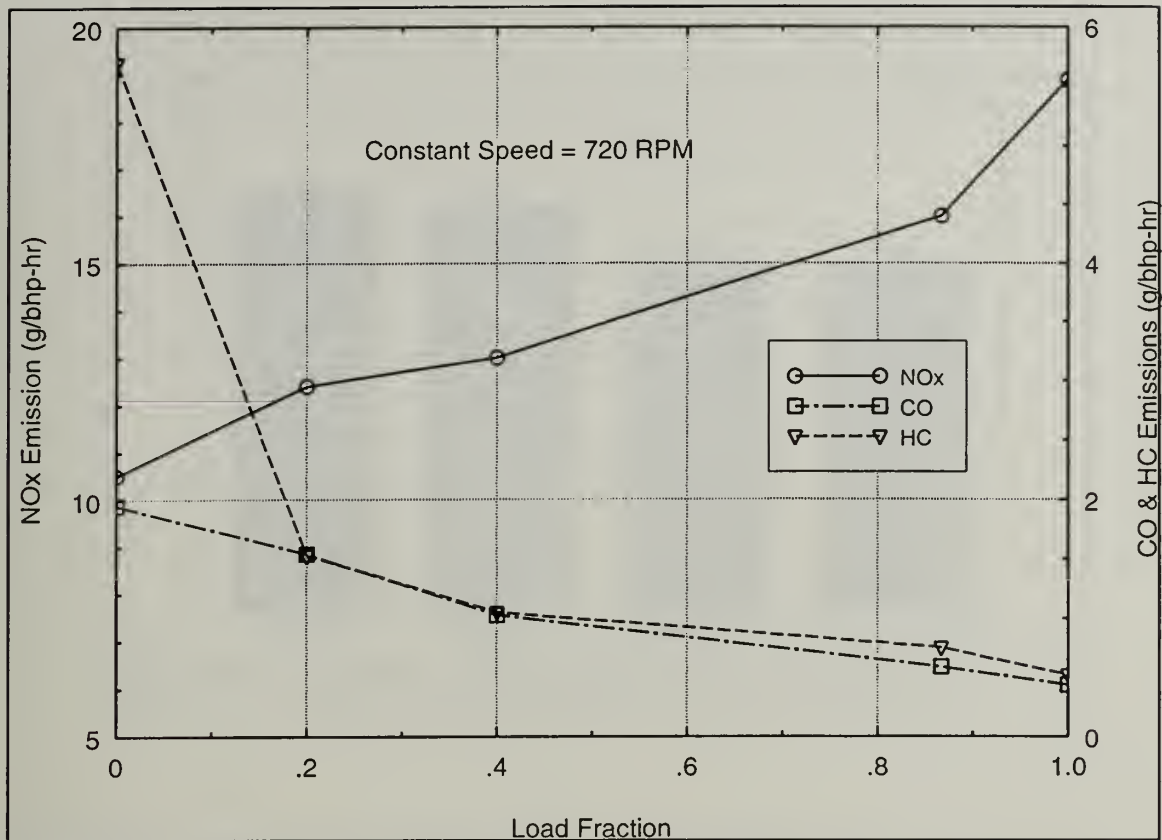


Figure 37: LSD 41 Class SSDG Exhaust Emission Curves

The curves of Figure 37 were used to determine emission data for the three industry constant speed duty cycles and the LSD 41 Class SSDG Duty Cycle. Summary emission data for the four duty cycles appears in Table 4-4.

Table 4-4: SSDG Duty Cycle Emission Prediction Summary (g/bhp-hr)

Prediction Method	NO _x	J. NO _x	CO	HC
DEMA Duty Cycle	16.4	14.0	0.6	0.7
ISO D1 Duty Cycle	16.0	14.0	0.7	0.8
ISO D2 Duty Cycle	13.7	14.0	1.0	1.3
LSD 41 Duty Cycle	13.6	14.0	0.9	1.1

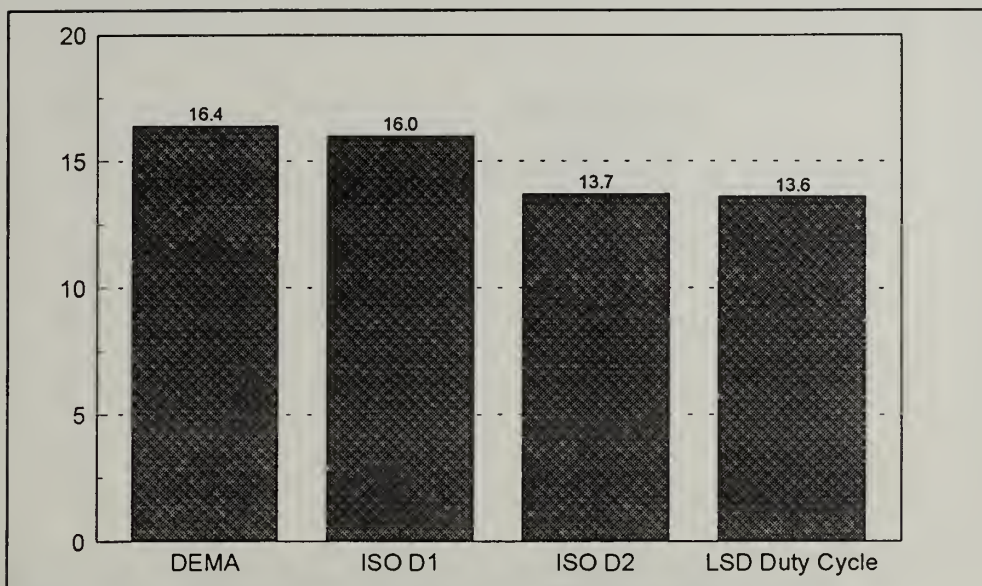


Figure 38: SSDG NO_x Prediction Comparison (g/bhp-hr)

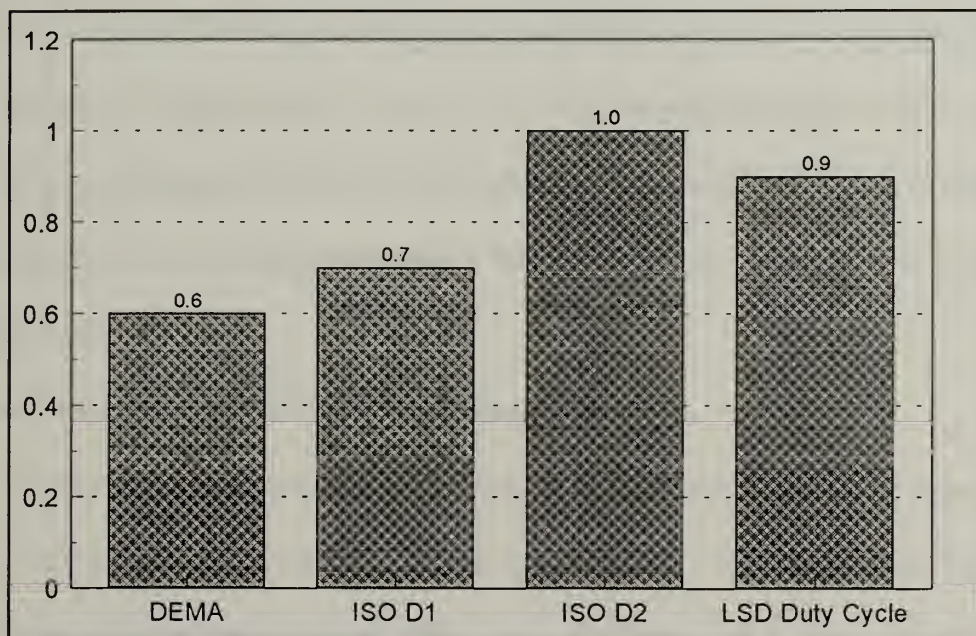


Figure 39: SSDG CO Prediction Summary (g/bhp-hr)

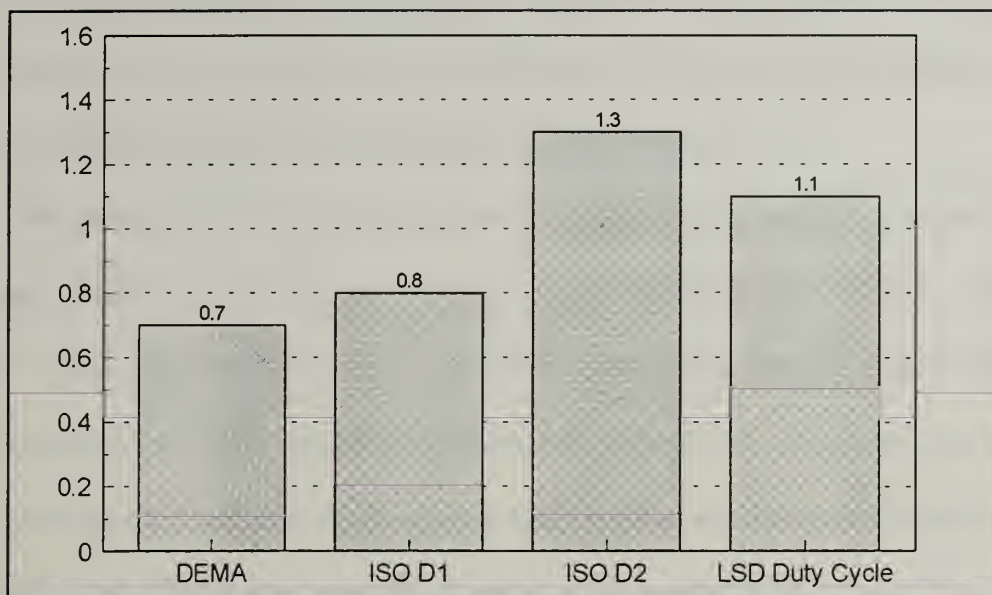


Figure 40: SSDG HC Prediction Comparison (g/bhp-hr)

The graphs of Figures 38 to 40 clearly indicate that the DEMA and ISO 8178-4 D1 Duty Cycles are inappropriate for modeling LSD 41 Class SSDG operation. ISO 8178-4 D2 provided the closest approximation to that calculated using the LSD 41 Class SSDG Duty Cycle. The identical prediction for NO_x made by the Japanese Formula was surprising. The observed range of engine speed values and time factors adding to the identical emission value is most probably coincidental.

4.5 Duty Cycle Conclusions and Applications

A duty cycle must provide an accurate correlation/prediction of actual emissions performance over some range of operation. The range of operation will include different applications that must be modeled individually. To facilitate the ship design process, a two step procedure for engine emission certification is

proposed. First, prequalify the engine at the same time the Endurance Test is performed by measuring emissions at Endurance Test speed/power points. Second, certify the engine after matching engine to hull form.

Naval ship designers choose main propulsion engines from a list of those that have passed the endurance test and receive certification. Table 4-2 and Table 4-3 indicate that the U.S.N. Endurance Test points provide a reasonable approximation of engine emission performance for LSD 41. However, the best duty cycle for emissions is not the same one for wear and endurance testing. To facilitate naval ship design candidate diesel engines should continue to be tested via Military Specification MIL-E-23457B for endurance and wear. Engine emission measurements should be taken concurrently. The U.S.N. Endurance Test continues for 1,000 hours offering ample time to measure engine emissions under steady state conditions. The emissions test procedure should follow the guidelines of ISO 8178. Concurrent emission measurement done in this manner should not present a burden to the engine manufacturer.

Emission data derived from the Endurance Test would form the basis for engine certification by the Navy. After marrying a specific hull design with a certified engine, emission prediction refinement, using the procedure of Figure 18, would be required. The environmental impact statement prepared by the ship program manager should reflect the refined emission prediction. Figure 41 illustrates the procedural steps for qualification of a diesel MPE for use on a specific new naval vessel design. Existing naval ship MPE's should be tested at

speed/power points and time factors derived from Figure 18, using ISO 8178-2 for procedural guidance.

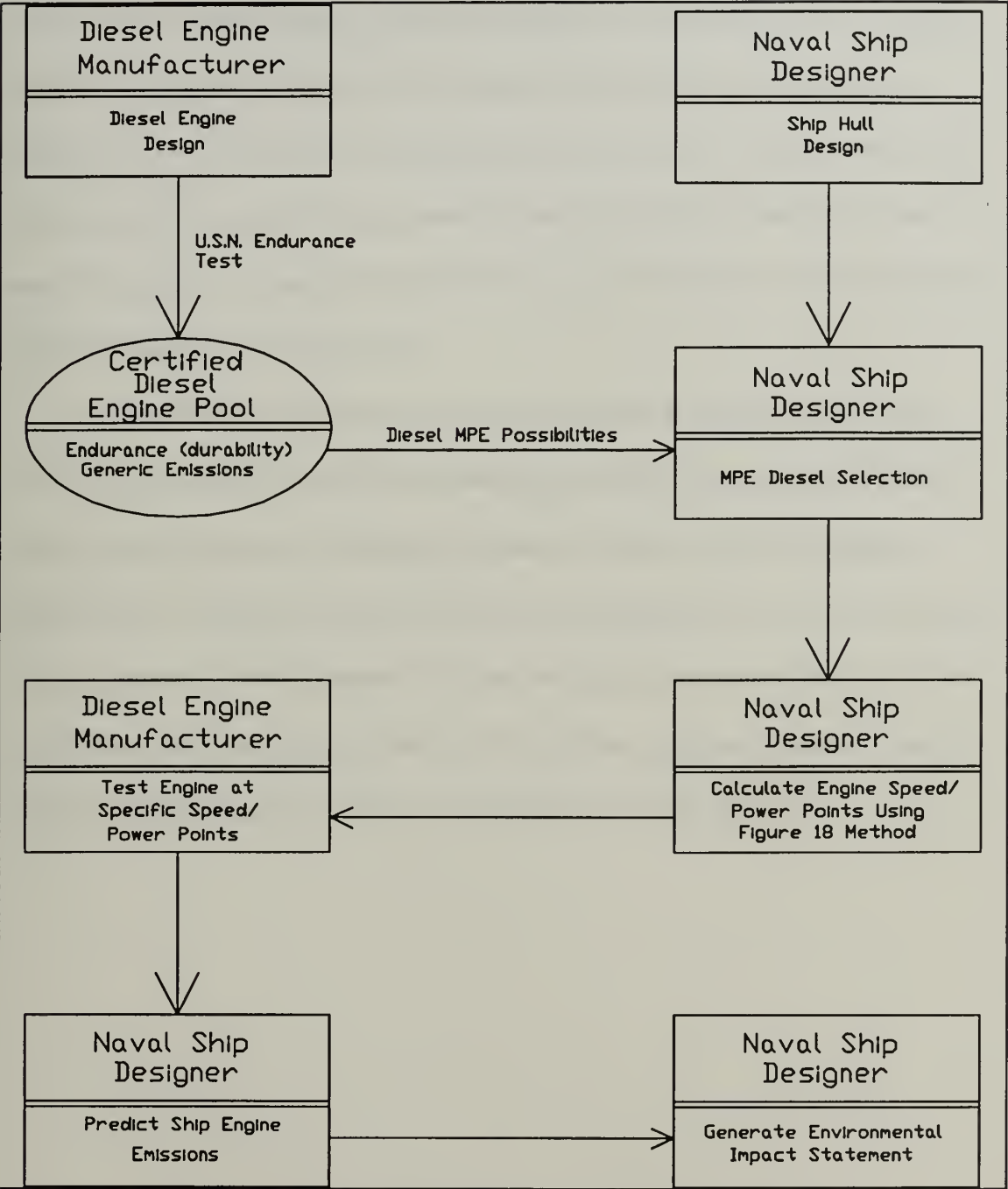


Figure 41: New Ship Design MPE Emission Certification Process

Ship service diesel engines should be exhaust emission pre-qualified and final emission certified using a procedure similar to that illustrated in Figure 41. In the case of constant speed diesel generators, it is probable that a modified ISO 8178-4 duty cycle D2 could be adopted by the Navy for final emission certification. The time factors (weight factors) of D2 can be readily modified to match actual ship operation by cursory review of the ship's Electrical Division logs. Procedural guidance of ISO 8178-1 for bench testing and ISO 8178-2 for shipboard testing should be used.

The method advocated in the California Federal Implementation Plan (CFIP) to calculate NO_x based solely on engine speed is oversimplified to the point of presenting grossly inflated estimates of engine exhaust emission performance. Tables 4-2 and 4-4 indicate over estimations of up to 100 percent. The procedure given in Chapter 3 and the evaluation presented in this chapter provide a simple, yet accurate method for predicting engine emissions based upon the actual operating profile of naval diesel powered ships.

CHAPTER 5: STACK EMISSION MEASUREMENT

Within the engine exhaust stack chemical transformation of diesel engine exhaust gases may occur. The exhaust stack system is defined as the system through which engine exhaust gases pass from the engine turbocharger exit to the atmosphere. Chemical processes occurring within the stack are primarily dependent upon residence time and stack temperature. Residence time within the stack is determined by stack length and gas velocity. The analysis detailed in this chapter utilizes the LSD 41 Class stack design.

5.1 LSD 41 Class Stack Description

Each propulsion engine has two turbochargers. Exhaust from each turbocharger is combined into a common header. Headers from each engine are run to, and up, the port and starboard uptakes. In the uptakes, each header is connected to an exhaust silencer which reduces airborne noise from each engine. The outlet of the exhaust silencer is connected to an exhaust pipe which continues to the atmosphere. The exhaust system piping is composed of stainless steel piping with a wall thickness of 0.188 inches. It's inner diameter is 2.14 feet at the inlet and 2.97 feet at the exit. The stack is approximately 127 feet in length, with total flow head loss calculated as 0.40 psi. Figure 42 illustrates the plan view²⁵, and Figure 43 the profile view²⁶, of the LSD 41 Class stack for the starboard main propulsion engines (MPE IA & IB). Table 5-1

²⁵NAVSEA Drawing 835-4799873, p. 8.

²⁶Ibid., p. 9.

provides the stack inlet and outlet conditions.²⁷

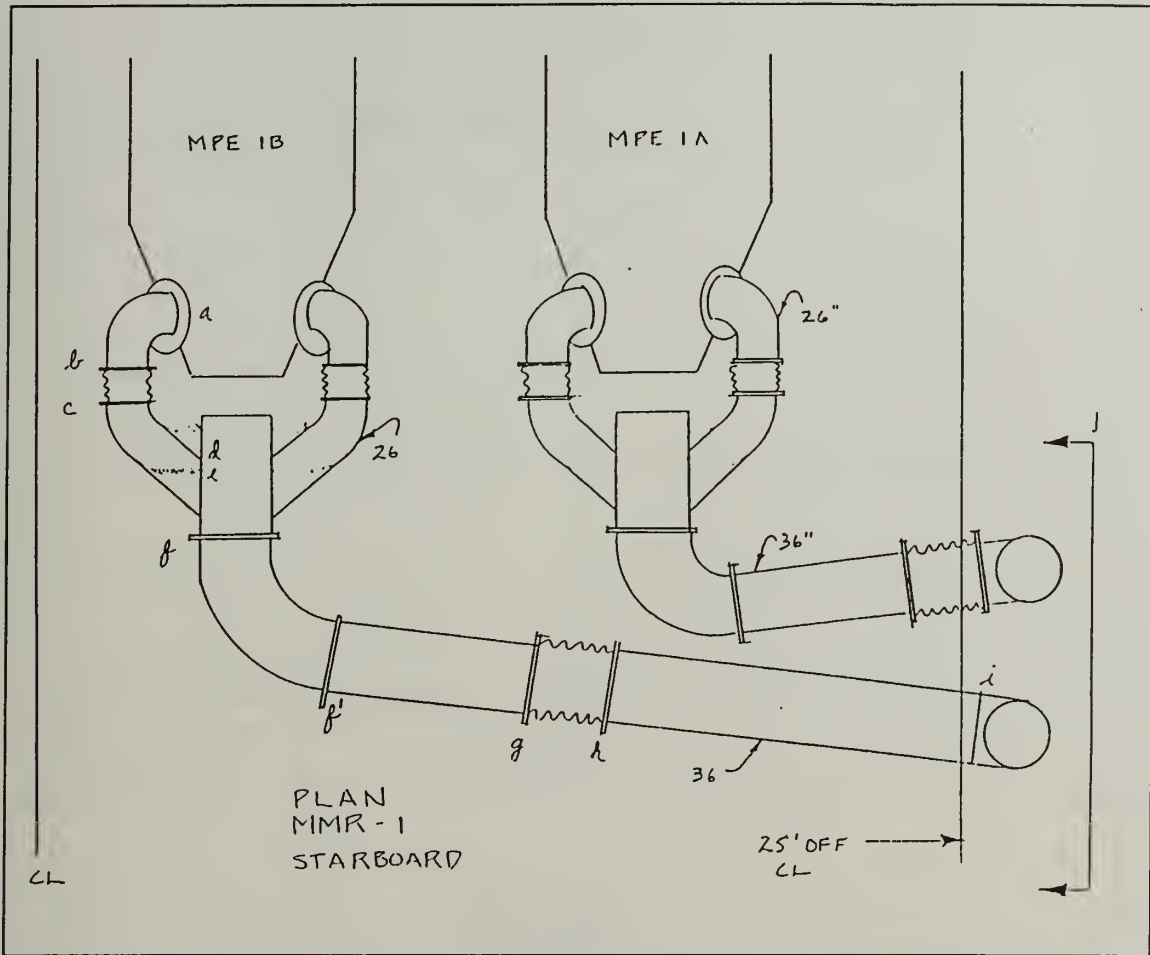


Figure 42: LSD 41 Class Starboard MPE Exhaust System - Plan View

²⁷NAVSEA Drawings 259-4799872 and 835-4799873.

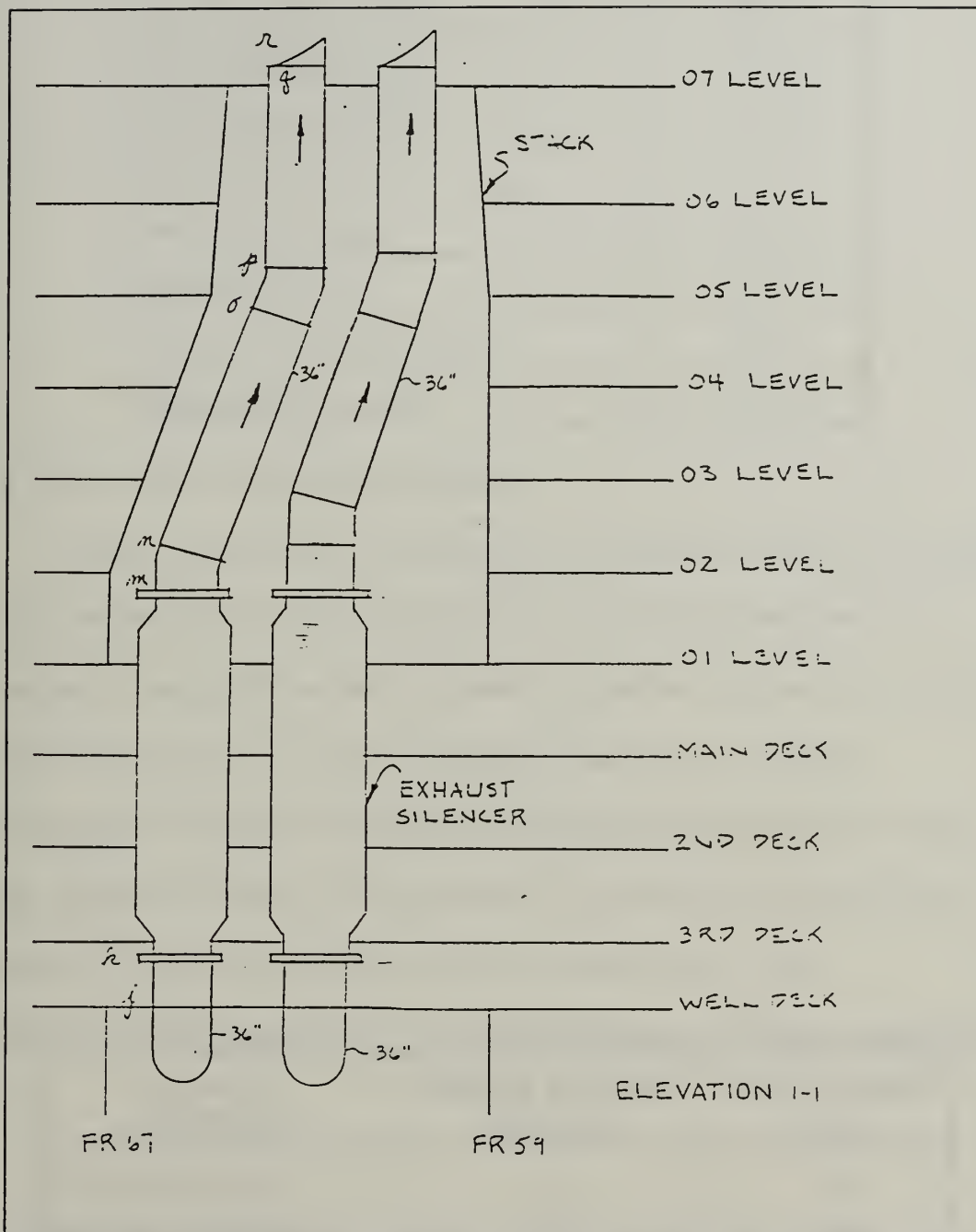


Figure 43: LSD 41 Class Starboard MPE Exhaust Stack - Profile View

Table 5-1: Exhaust Stack Flow Parameters

Parameter	Value
Inlet Temperature (°K)	688.7
Exit Temperature (°K)	688.7
Inlet Velocity (m/sec)	40.86
Exit Velocity (m/sec)	42.27
Inlet Pressure (psi)	25.0
Exit Pressure (psi)	24.6
Volume Flow Rate (m ³ /sec)	1631.1
Residence Time (sec)	0.92

5.2 Exhaust Gas Constituent Analysis

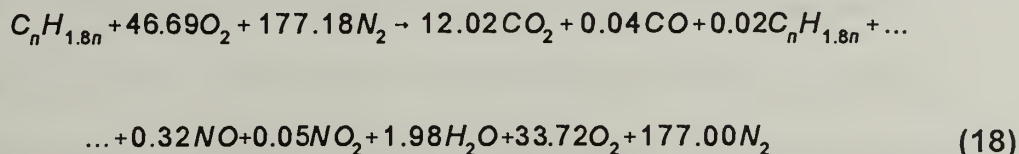
Table 4-2 provided the 11-Mode LSD 41 Class Duty Cycle MPE exhaust specific emission predictions in units of grams per brake horsepower-hour. Analysis of chemical processes is facilitated by species representation in units of concentration (ppm). Conversion of specific emissions to volumetric concentrations requires specification of operating condition and time at that state. Operation at rated power and speed for one second was selected for analysis. Table 5-2 provides the gaseous emission levels studies.

Table 5-2: Colt-Pielstick 16 PC-2.5 V400 Emissions at Rated Conditions²⁸

Gaseous Constituent	Specific Emission (g/bhp-hr)	Concentration (ppm)
Carbon Monoxide	0.8	155
Oxides of Nitrogen	9.0	1749
Hydrocarbons	0.2	39

²⁸Letter dated 19 October 1993 from G. Monahan, Coltech Industries.

Table 5-2 data was then used to write the chemical equation describing the combustion of diesel fuel within the PC-2.5 engine at equivalence ratio of 0.38. Oxides of nitrogen were assumed to be made up of 90 percent NO and 10 percent NO₂. Equation 18 gives the chemical equilibrium condition for this combustion process.



The hydrocarbon fuel, C_nH_{1.8n}, was approximated by C_{12.3}H_{22.4} where n=12.3. This approximation was made since diesel fuel is a mixture of hydrocarbon compounds which have an overall molecular weight of approximately 170. For analysis purposes, the exhaust gaseous hydrocarbon was assumed to be made up of the chemical compounds listed in Table 5-3²⁹.

Table 5-3: Exhaust Gaseous Hydrocarbon Constituents

Family	%	Modeled As	Formula	# Moles (E-3)	Grams
Paraffins	36	Ethane	C ₂ H ₆	5.7	0.171
Cycloparaffins	40	Cyclobutane	C ₄ H ₈	3.91	0.219
Olefins	9	Propene	C ₃ H ₆	1.00	0.043
Other	15	Not Modeled	*	0.00	0.000

The chemical compounds listed under "Other" in Table 5-3 consist of Indans and Tetralins (5%), Indene (1.3%), Naphthalene (4.4%), Acenaphthylene (4.0%), and

²⁹Gaseous hydrocarbon composition is consistent with Table 17 of Fossil Fuel Combustion A Source Book by William Bartok and Adel F. Sarofim, John Wiley & Sons, 1991, p. 43.

Tricyclicaromatics (0.3%). Due to their minor contribution to the overall composition of diesel fuel, and limitations on the combustion model employed, "Other" hydrocarbons were not modeled.

Exhaust gas analysis was performed by using Sandia Labs computer software package *CHEMKIN* to model exhaust gas composition changes within the stack. *CHEMKIN* is a *FORTTRAN* chemical kinetics code designed to facilitate simulations of elementary chemical reactions in flowing systems. *CHEMKIN* solves the stiff differential equations describing a particular set of boundary conditions and chemical species present. User inputs include: elements, species, Arrhenius reaction rate coefficients, boundary conditions and reaction time span. Arrhenius reaction rate coefficients describe the rate at which a chemical reaction takes place. For example, oxidation of carbon monoxide (CO) to carbon dioxide (CO₂) is given by Equation 19.



The rate at which carbon monoxide and oxygen react to form carbon dioxide is governed by the Arrhenius expression of the form of equation 20.

$$k = A T^b \exp\left(-\frac{E}{RT}\right) \quad (20)$$

The reaction rate (*k*) is dependent upon activation energy (*E*), temperature (*T*), gas constant (*R*), and Arrhenius coefficients *A* and *b*. The reaction rate of Equation 19 is given by Equation 21.

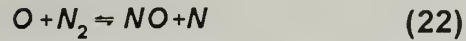
$$k = 1.60E13 \times T \times \exp\left(\frac{-41,000}{1.987 \times T}\right) \quad (21)$$

A in Equation 21 is in units of mole-cm-sec-K and E in units of cal/mole.

The *Intrepeter* program of *CHEMKIN* reads the symbolic description of the chemical reaction mechanisms to be studied. *Interpreter* then provides a linking file to the 100 module *Gas-Phase Subroutine Library*. This library returns information on equation of state, thermodynamic properties, and chemical production rates.³⁰ Appendix D provides the input file and interpreter file which lists the chemical reactions and species studied.

Gas-Phase Subroutine solves the differential equations which describe chemical species rate of change. For example, the production of NO during the combustion process occurs by three principle means: thermal, prompt, and fuel-bound mechanisms. The thermal NO formation mechanism is the extended thermal or Zeldovich reaction system of equations. NO formation at temperatures above 1000° K increases exponentially; but at lower temperatures the reaction rate is very slow. Equations 22 to 24 give the Zeldovich reaction scheme.

³⁰Robert J. Kee, et. al., "CHEMKIN-II: A Fortran Chemical Kinetics Package for the Analysis of Gas-Phase Chemical Kinetics," Sandia National Laboratories, December 1990, pp. 3-10.



Estimation of NO concentration requires knowledge of the temperature and concentrations of other species. Analysis is simplified by assumption of equilibrium conditions existing between the reaction products. Reaction rate constants for forward and reverse reactions of Equations 22 to 24 must be known in order to determine the change in NO concentration over time. The rate change of NO concentration is given by Equation 25.

$$\frac{d[NO]}{dt} = 2k_{22}[O][N_2] \frac{1 - \frac{[NO]^2}{K_e[O_2][N^2]}}{1 + \frac{k_{-22}[NO]}{k_{23}[O_2] + k_{24}[OH]}} \quad (25)$$

Where K_e is the equilibrium constant for the production of NO from the oxidation of atmospheric nitrogen (N_2) by oxygen (O_2). The reaction coefficients are given in Fundamentals, Modeling and Computations in Reacting Flows and Combustion, by A. F. Ghoniem, 1993, p. 2-41.

Exhaust gas flow reactions were modeled by 164 reaction mechanisms involving 38 chemical species. Several assumptions were made to simplify the analysis:

1. High volume flow rate and low residence time in the stack minimize heat transfer between gas flow and stack piping. Therefore, adiabatic constant

enthalpy conditions were assumed.

2. The gas stream was modeled as a well stirred reactor due to the significant amount of mixing occurring post combustion.

3. The gas was modeled as a plug flow system allowing Lagrangian description.

4. Species listed in Table 5-3 and Appendix D were appropriate for modeling the gaseous unburned diesel fuel.

5. Particulate emissions were assumed to be inert. Therefore, chemical reactions between gaseous species and particulate matter were ignored.

Results of the *CHEMKIN* model are displayed in Figure 44. It is readily apparent that the low temperature within the flow, 688.7°K, and short residence time of 0.92 seconds was insufficient to allow significant oxidation of unburned gaseous hydrocarbon. Reactivity of the species in the exhaust stream, as modeled by the Arrhenius chemical reaction rate coefficients, were insensitive to the temperature within the stack. NO_x concentrations, as well as all others, were frozen at exhaust manifold levels.

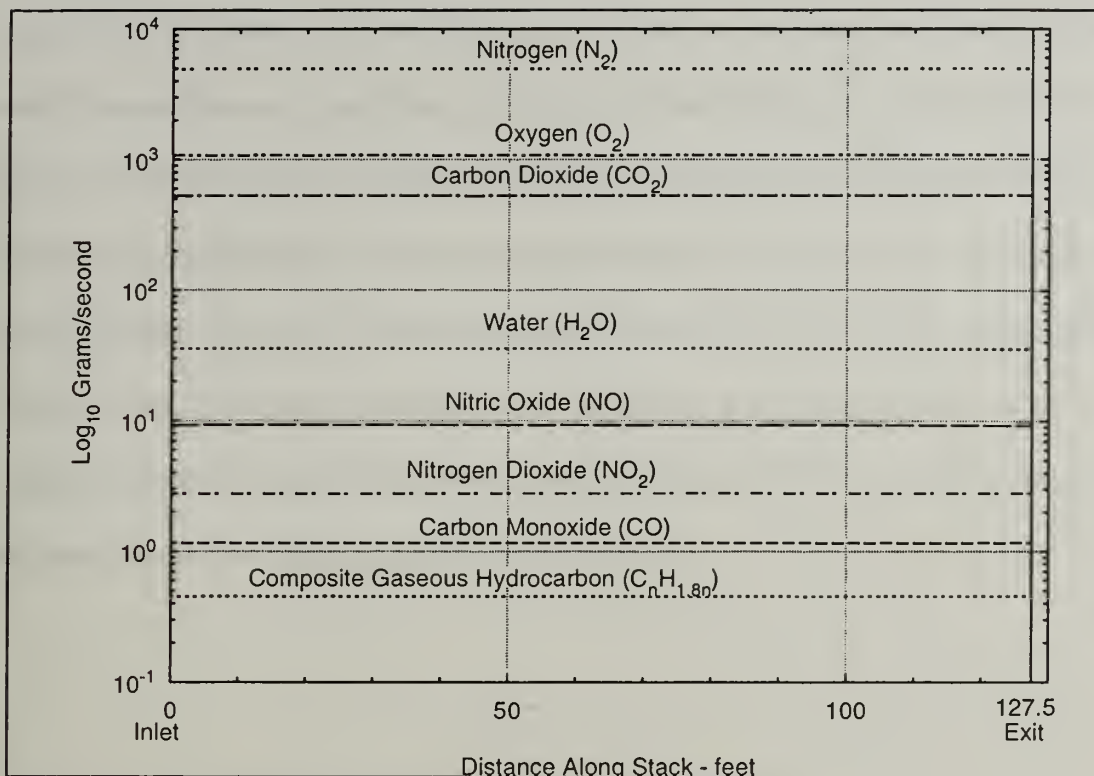


Figure 44: CHEMKIN Exhaust Stack Model

5.3 Ship Emission Measurement

Figure 44 shows gaseous concentrations do not change significantly within the exhaust stack; in fact exhaust stack chemistry is frozen at inlet concentrations. The LSD 41 Class is well suited for engine exhaust emission measurement. Engine operating console in each main machinery room provides analog output of: engine RPM, shaft torque, shaft RPM, fuel flow rates, and engine temperatures and pressures.

Instrumentation of the inlet plenum and exhaust stack would be required to determine gas flow parameters. Inlet gas conditions may be modeled by turbocharger performance. Exhaust measurements may be taken where most

convenient. Exhaust measurement at turbocharger and stack exit locations are readily accessible and could be used with minimum impact on ship operations. Existing inspection covers could be modified to accept the sampling probe, or special boss type fittings installed in the stainless steel piping itself. Portable gas analyzers, such as the ENERAC 2000E used during the USCG cutter *Point Turner* testing, offer data collection and analysis in a compact format. Data collecting should be performed to simultaneously record ship propulsion plant parameters and resulting engine emission levels.

Chapter 6: Conclusions and Recommendations

The U.S. Navy, Naval Sea Systems Command Code 03X3, published *Internal Combustion (Gas Turbine and Diesel) Engine Exhaust Emission Study* in 1991. On page 6-1 of this study, the following observation is made: "Before the Navy can begin an emission test program it must decide the test points for which to collect emission data..." This thesis recommends a methodology for determining the test points for diesel powered ships.

Log review, used in preparing this thesis, offers a method to develop ship operating profiles which formed the basis for developing engine duty cycles. This approach expended approximately 600 man-hours. Although this method provided reasonable and consistent results it is recommended that NAVSEA instrument two LSD 41 Class ships (one on each coast) to validate the operating profile derived by log review. Ships should be instrumented for six months and should include emission measurements taken at convenient intervals. These measurements could be used to confirm the emission estimates developed in this thesis. After validation, operating profiles and emission estimates for other naval diesel ship classes should be derived by log review and prediction methods developed in this thesis. Engine exhaust emissions should be calculated for each ship type. Following ship emission determination, comparison with emission limits can be made and strategies for ship engine emission reduction studied for their interdependence and effect on naval ship operations.

CARB proposed NO_x emission limits for existing diesel powered ships is 600 ppm. U.S. Naval vessels are currently exempt from this policy. Future regulations may require naval ship compliance. Development of specific engine emission contour maps requires many hours of costly engine operation on the test stand. NO_x emission concentrations of 565 ppm over a 24 hour period were predicted in this research using the LSD 41 Class Duty Cycle and generic engine emission contour plots. Determination of actual Colt SEMT-Pielstick PC2.5 V400 diesel engine emissions at LSD 41 Class Duty Cycle points is recommended to certify LSD 41 Class emissions.

Industry standard duty cycles of ISO 8178-4, EPA and others were shown to be inadequate for estimation of naval ship engine exhaust emissions. The Navy should present the method outlined in Chapters' 3 and 4 to national and international regulatory organizations and classification societies (such as EPA, CARB, ISO, IMO, etc...) for adoption. In addition, the Navy should formalize the conclusions presented in Section 4.5 by adding them to Military Specification MIL-E-21260D, *Engines, Diesel Marine, Propulsion and Auxiliary, Medium Speed*, and its sister document for high speed diesel engines. The certification method advocated in this thesis is applicable to both MPE and SSDG engines.

Chemical kinetic computer routines, such as *CHEMKIN*, are useful in predicting chemical composition of diesel engine exhaust. Analysis indicated exhaust gas emitted from the stack is similar to that exiting the engine. Interaction between gaseous and particulate material, and particulate behavior

in the stack, is not well defined nor understood; therefore, further research is warranted. This can be accomplished in three ways: in the lab, through instrumentation of ship exhaust stack, or through use of more sophisticated computer codes possessing the ability to model a greater number of gaseous and particulate species and reactions.

Future work should consider engineering remedies and cost benefit analysis to optimally reduce engine emissions. Possible solutions have been discussed in Section 1.4. However, each solution may have an impact on others. For example, reduced speed operation will lessen NO_x production, but will also reduce the exhaust flow bulk temperature. Selective Catalytic Reduction (SCR) methods rely on temperatures at or above 800°F . When operated by current doctrine, diesel engine exhaust temperatures are typically very near this temperature. Speed restriction would reduce exhaust flow temperature and therefore minimize the effectiveness of SCR. Other possible solution methods include the relocation of operating areas farther out to sea and implementation of designated transit lanes with near land speed restrictions. These solutions will have an impact on U.S. Navy operations. What seems a reasonable engineering solution to a given problem may be inadequate when viewed from the perspective of the ship operator. Complete analysis of the interaction between proposed solutions and associated costs must be performed.

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Appendix A: Sample Ship Log Data Sheets

This appendix contains blank sample ship log sheets representative of those reviewed to develop the LSD 41 Class operating profile described in Chapter 2.

[illegible]

Figure A-1: Ships Deck Log Sheet

Figure A-2: Engineering Smooth Log Sheet

Appendix B: Ship Visit Summaries

This appendix provides summaries of ship, coast, and four ship cumulative MPE time factors supporting the LSD 41 Class Operating Profile development of Chapter 2. The data of Table 2-7 is repeated here for appendix completeness.

Table B-1: LSD 41 Class Ship Data Summary (All Times in Minutes)

	LSD 43	LSD 44	LSD 46	LSD 47
Name	Fort McHenry	Gunston Hall	Tortuga	Rushmore
Coast	West	East	East	West
Time Period (1993)	12 July 16 December	14 September 30 November	3 March 20 September	1 June 16 December
Main Propulsion Engine Data				
Data Points	5,011	2,816	4,267	3,013
Time Covered	252,324	133,052	159,845	145,517
Time Secured	74,589	54,499	76,872	51,025
Time Running	177,735	78,553	82,973	94,492
Time Warmup	1,458	1,306	1,892	1,571
Time @ Idle	2,886	1,725	2,357	1,155
Time @ Power	173,391	75,522	78,724	91,766
Ship Service Diesel Engine Data				
Data Points	992	414	862	809
Time Covered	239,750	146,895	210,854	182,942
Time Secured	66,127	38,516	90,442	55,328
Time Running	173,623	108,379	120,432	127,614
Time Warmup	1,602	1,664	2,101	3,065
Time @ Idle	1,039	4515	2,329	1,275
Time @ Power	170,982	106,300	116,002	123,274

The next five sections contain spreadsheet time summary sheet and graphic summaries for: each ship, by coast, and overall composite. The spreadsheet columns are mostly self explanatory. However, some explanation is required.

- The LSD 41 Class has four MPE's, numbers 1A and 1B on the starboard shaft, and 2A and 2B on the port shaft.

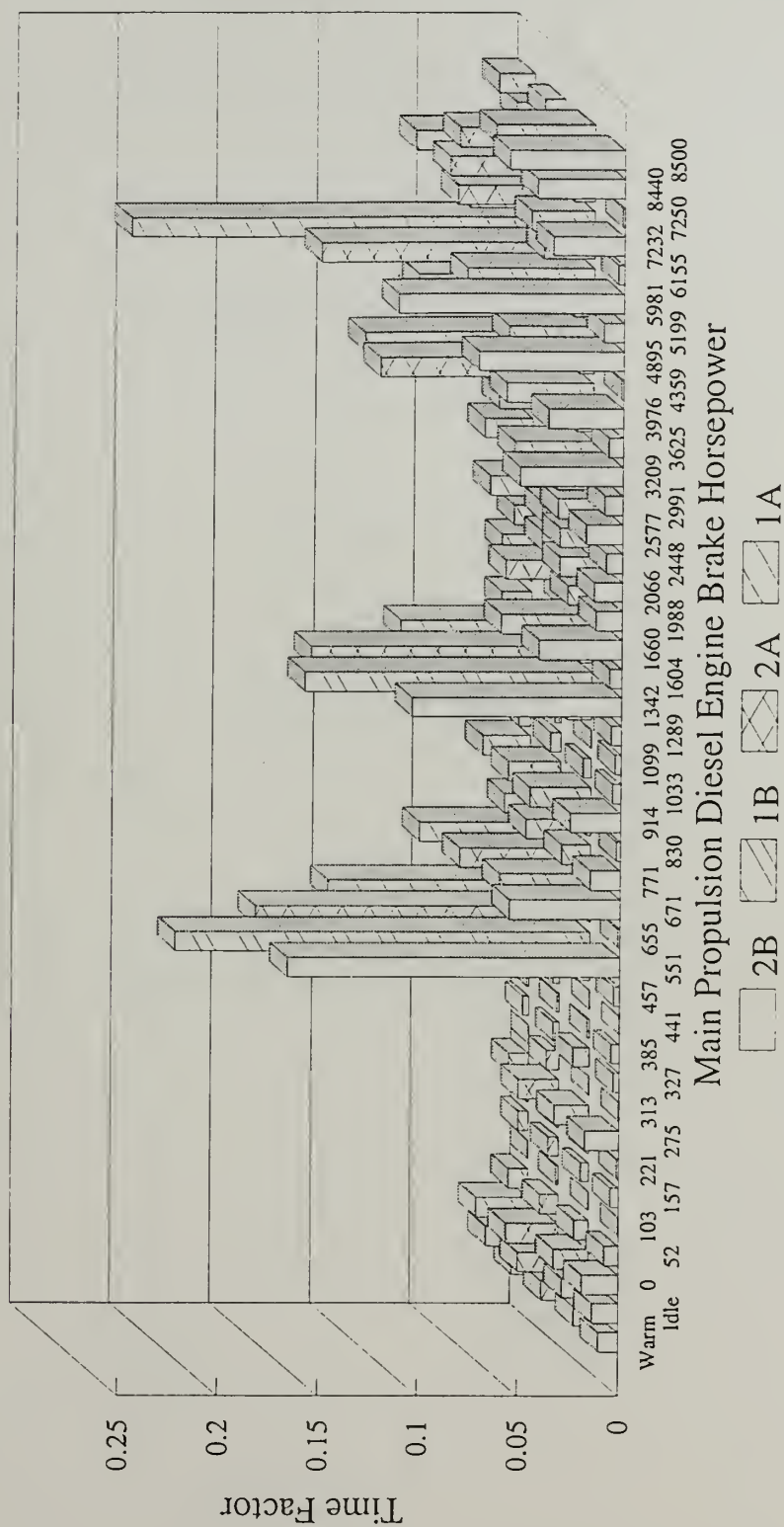
- The time values given are in minutes.

- "_n" indicates normalization to some value. Time values (i.e. 1A_n) are normalized to engine total time running. RPM and power are normalized to their rated values (520 and 8,500 respectively).

B.1: USS FORT McHENRY (LSD 43)

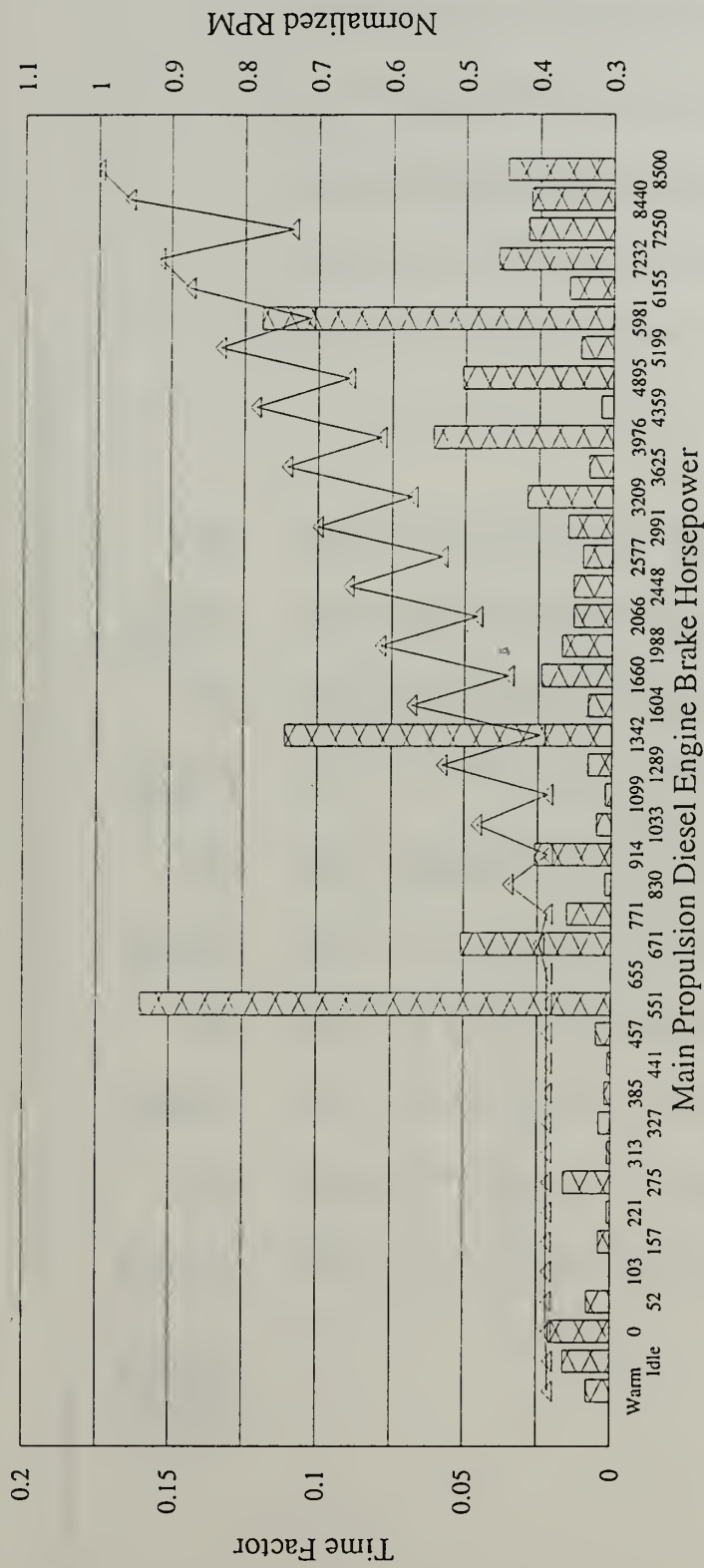
Table B-2: USS FORT McHENRY (LSD 43) MPE Data Summary

MPE Time Factor Calculations	1A	1A_n	1B	1B_n	2A	2A_n	2B	2B_n	Total	Total_n	Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n
Data Points:	1145		1345		1193		1328		5011	0.008			200	0.385	Warm	0
Total Time:	56708		64687		62328		68601		252324	0.016			200	0.385	Idle	0
Time Secured:	16916		14968		21660		19045		74589	0.021	All Stop	0	201	0.387		0.006
Time Running:	37792	1	49719		40668	1	49556	1	177735	0.008		2	201	0.387	52	0.012
Time Warming Up:	298	0.008	341	0.007	328	0.008	491	0.01	1458	0.008		1	201	0.387	103	0.018
Time at Idle:	783	0.021	652	0.013	794	0.02	657	0.016	2886	0.016		2	201	0.387	221	0.026
Time at Power:	36711	0.971	48726	0.98	39546	0.972	48408	0.977	173391	0.976		3	201	0.387	157	0.032
												4	201	0.387	275	0.037
												5	201	0.387	313	0.038
												6	201	0.387	327	0.038
												7	201	0.387	385	0.045
												8	201	0.387	441	0.052
												9	201	0.387	457	0.054
												10	201	0.387	551	0.065
												11	201	0.387	655	0.077
												12	201	0.387	671	0.079
												13	201	0.387	771	0.091
												14	201	0.387	830	0.098
												15	201	0.387	914	0.108
												16	201	0.387	1033	0.122
												17	201	0.387	1099	0.129
												18	201	0.387	1289	0.152
												19	201	0.387	1342	0.158
												20	201	0.387	1604	0.189
												21	201	0.387	1660	0.195
												22	201	0.387	1988	0.234
												23	201	0.387	2066	0.243
												24	201	0.387	2448	0.288
												25	201	0.387	2577	0.303
												26	201	0.387	2991	0.352
												27	201	0.387	3209	0.378
												28	201	0.387	3625	0.426
												29	201	0.387	3976	0.468
												30	201	0.387	4359	0.513
												31	201	0.387	4895	0.576
												32	201	0.387	5199	0.612
												33	201	0.387	5981	0.704
												34	201	0.387	6155	0.724
												35	201	0.387	7232	0.851
												36	201	0.387	7250	0.853
												37	201	0.387	8440	0.993
												38	201	0.387	8500	1
Total:	37792	1	49719	1	40668	1	49556	1	177735	1			200	0.385		



12 July - 16 December 1993

Figure B-1: LSD 43 Individual MPE Operating Profiles



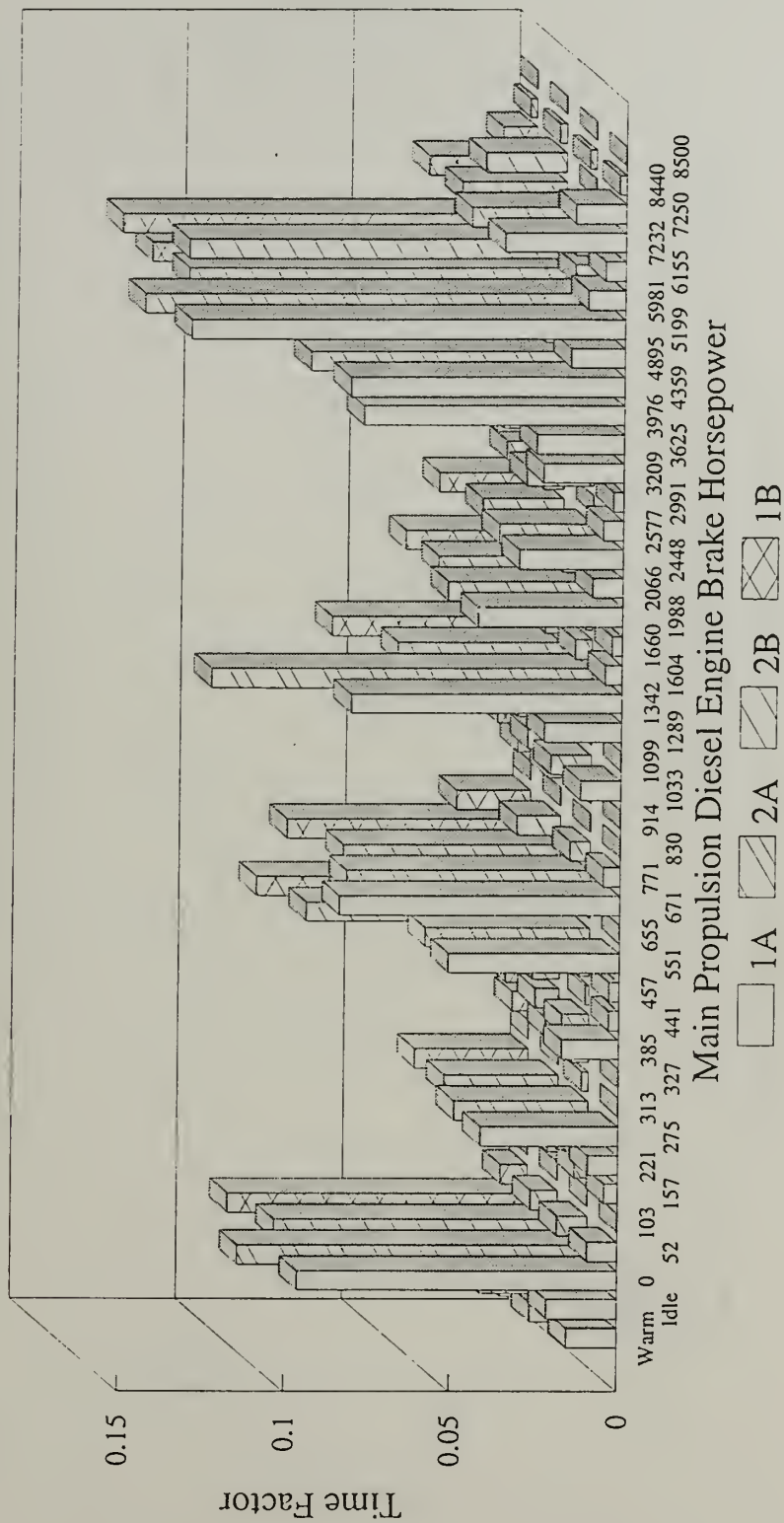
12 July - 16 December 1993

Figure B-2: LSD 43 Composite Operating Profile

B.2: USS GUNSTON HALL (LSD 44)

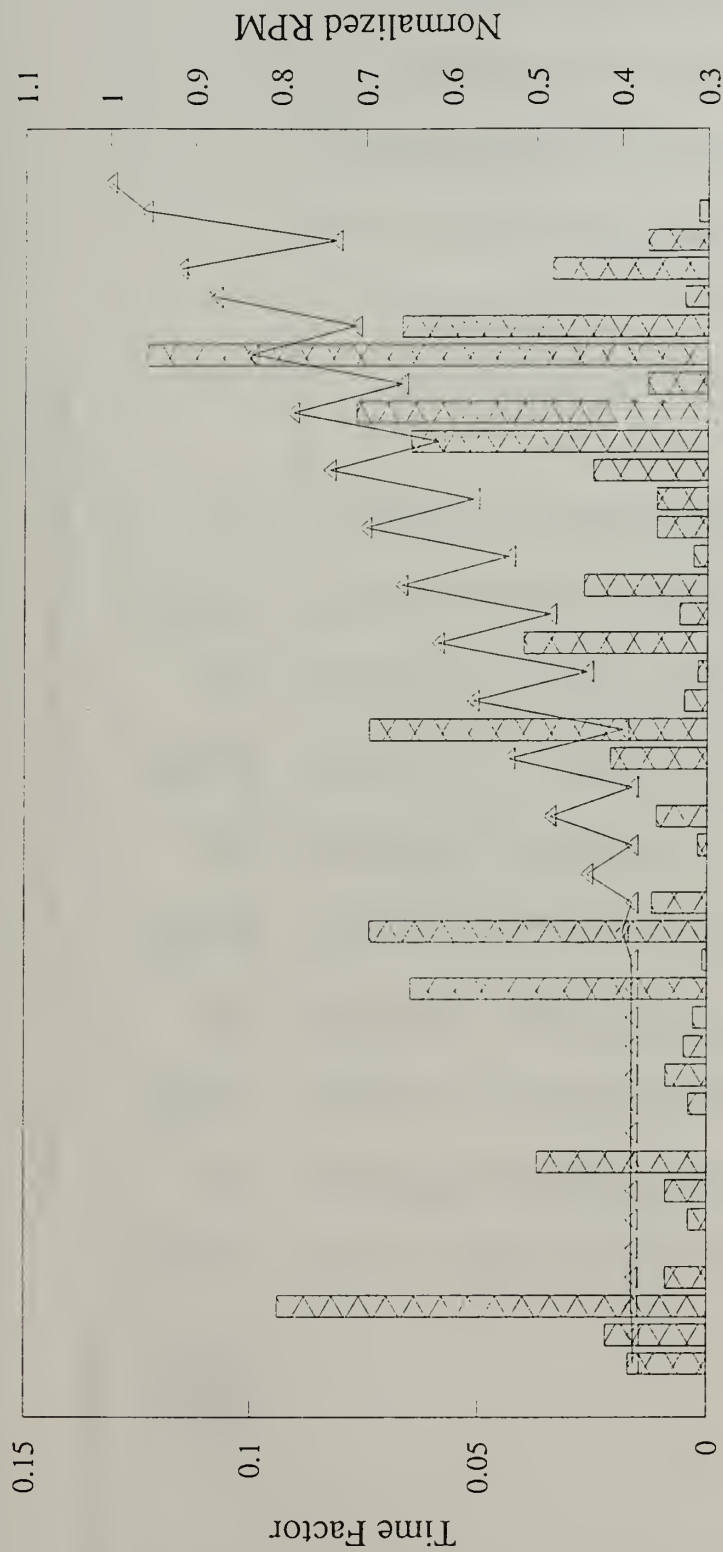
Table B-3: USS GUNSTON HALL (LSD 44) MPE Data Summary

MPE Time Factor Calculations																			
	1A	1A_n	1B	1B-n	2A	2A_n	2B	2B_n	Total	Total_n				Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n
Data Points:	695		704		689		728		2816									Warm	0
Total Time:	32419		33794		31159		35680		133052									Idle	0
Time Secured:	13887		12888		13301		14423		54489										
Time Running:	18532	1	20906	1	17858	1	21257	1	78553	1								52	0.006
Time Warning Up:	286	0.015	353	0.017	309	0.017	358	0.017	1306	0.017								103	0.012
Time at Idle:	396	0.021	380	0.018	563	0.032	386	0.018	1725	0.022								157	0.018
Time at Power:	17850	0.363	20173	0.965	16986	0.951	20513	0.965	75522	0.961								221	0.026
																		275	0.032
																		313	0.037
																		327	0.038
																		385	0.045
																		441	0.052
																		457	0.054
																		551	0.065
																		655	0.077
																		671	0.079
																		771	0.091
																		830	0.098
																		914	0.108
																		1033	0.122
																		1099	0.129
																		1289	0.152
																		1342	0.158
																		1604	0.189
																		1660	0.195
																		1988	0.234
																		2065	0.243
																		2448	0.288
																		2577	0.303
																		2991	0.352
																		3209	0.378
																		3625	0.426
																		3976	0.468
																		4359	0.513
																		4895	0.576
																		5199	0.612
																		5981	0.704
																		6155	0.724
																		7232	0.851
																		7250	0.853
																		8440	0.993
																		8500	1
Total:	18534	1	20906	1	17858	1	21257	1	78555	1									



14 September - 29 November 1993

Figure B-3: LSD 44 Individual MPE Operating Profiles



Main Propulsion Diesel Engine Brake Horsepower

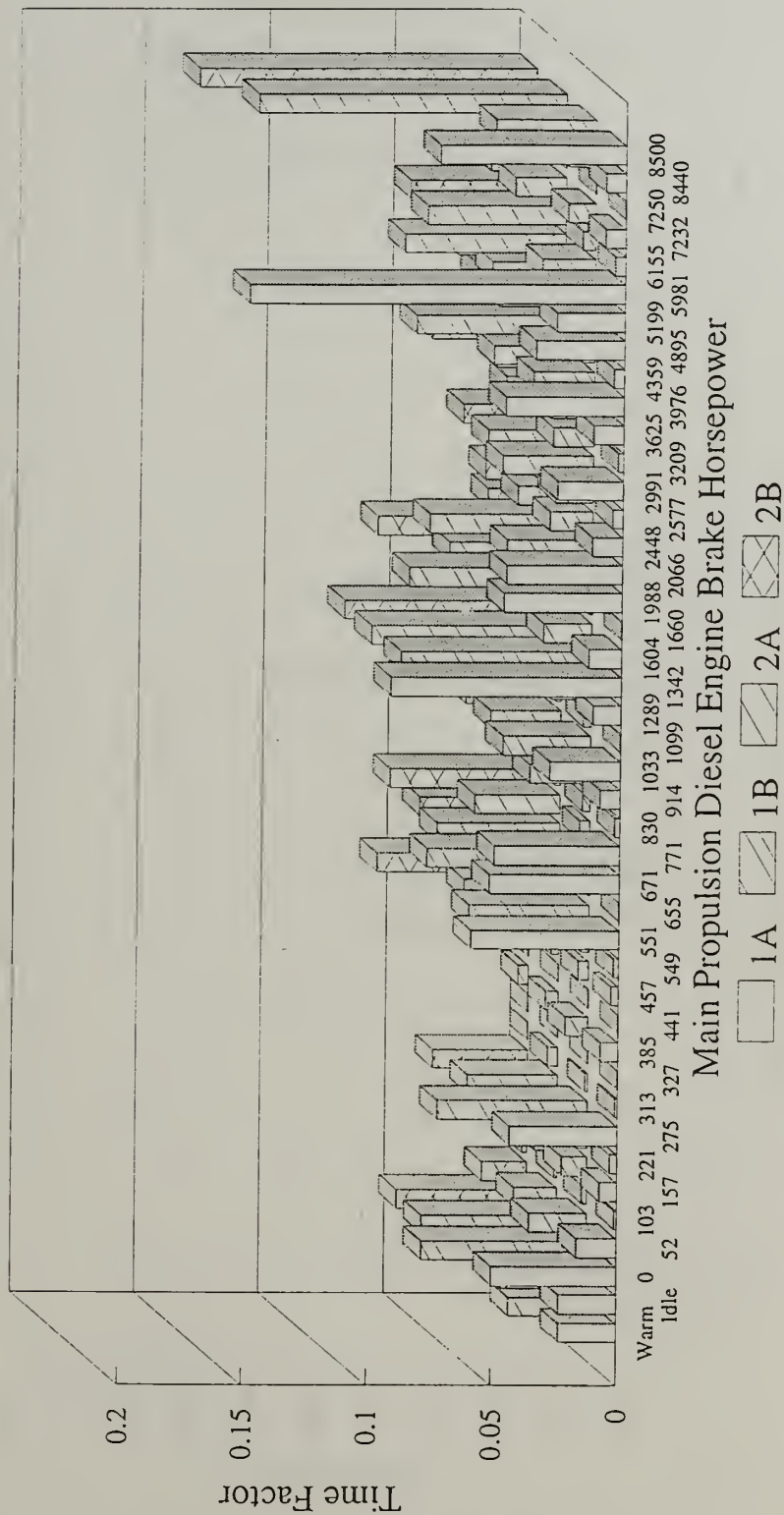
14 September - 29 November 1993

Figure B-4: LSD 44 Composite Operating Profile

B.3: USS TORTUGA (LSD 46)

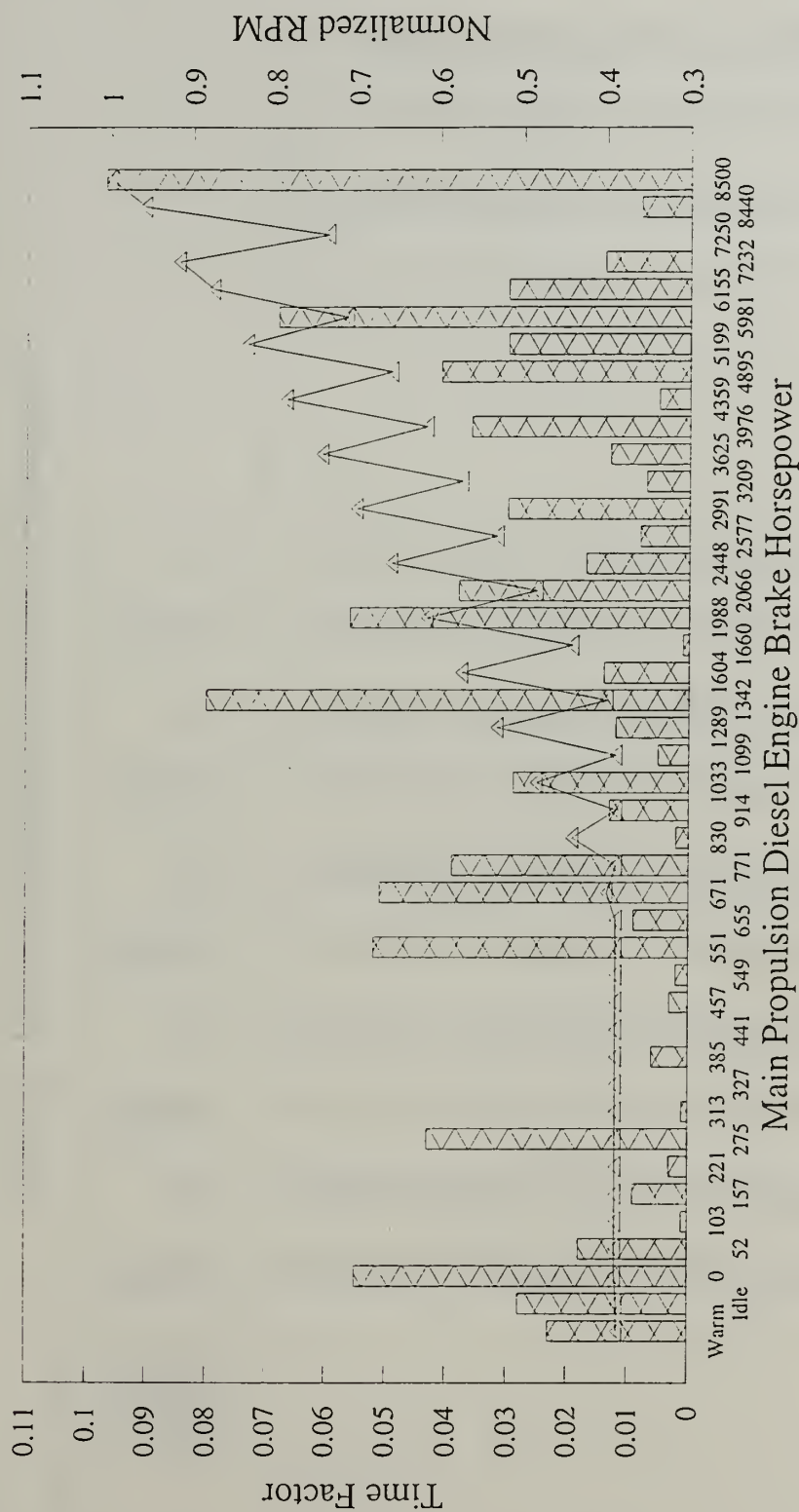
Table B-2: USS TORTUGA (LSD 46) MPE Data Summary

MPE Time Factor Calculations		IA	IA_n	1B	1B_n	2A	2A_n	2B	2B_n	Total	Total_n	Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n
Delta Points: • Total Time: Time Secured: Time Running: Time Warming Up: Time at Idle: Time at Power:	1056			1026		1033		1152		4267							
	43329			34985		39539		41992		159845						Warm	0
	20732			18945		18502				76872						Idle	0
	22597		1	16040	1	21037	1	23299	1	82973	1					52	0.006
	521	0.023		501	0.031	422	0.02	448	0.019	1892	0.023					103	0.012
Total:	531	0.023		551	0.034	662	0.031	613	0.026	2357	0.028					157	0.018
	1127	0.05		1064	0.066	1137	0.054	1209	0.052	4537	0.055	All Stop				221	0.026
	366	0.016		366	0.023	359	0.017	424	0.018	1515	0.018					275	0.032
	19	0.001		36	0.002	12	0.001	55	0.002	122	0.001					313	0.037
	160	0.007		159	0.01	179	0.009	226	0.01	724	0.009					327	0.038
	71	0.003		71	0.004	53	0.003	69	0.003	264	0.003					385	0.045
	968	0.043		967	0.06	762	0.036	863	0.038	3560	0.043					441	0.052
	22	0.001		11	0.001	81	0.004	3	0	117	0.001					549	0.065
	10	0		6	0	10	0	6	0	32	0					551	0.065
	152	0.007		152	0.009	103	0.005	103	0.004	510	0.005					655	0.077
	11	0		0	0	8	0	3	0	22	0					771	0.079
	60	0.003		60	0.004	58	0.003	66	0.003	244	0.003					830	0.098
	41	0.002		41	0.003	53	0.002	53	0.002	188	0.002					914	0.108
	1325	0.059		774	0.048	793	0.038	1421	0.061	4313	0.052					1033	0.122
	0	0		357	0	75	0.004	282	0.012	714	0.009					1289	0.152
Total:	1164	0.052		1039	0.065	1038	0.049	1024	0.044	4265	0.051					1342	0.158
	1135	0.05		63	0.004	711	0.034	1303	0.056	3212	0.039					1604	0.189
	51	0.002		51	0.003	51	0.002	51	0.002	204	0.002					1660	0.195
	170	0.008		384	0.024	327	0.016	227	0.01	1108	0.013					1988	0.234
	625	0.028		555	0.035	589	0.028	611	0.026	2380	0.029					2066	0.243
	0	0		46	0.003	34	0.002	362	0.016	442	0.005					2448	0.288
	253	0.011		253	0.016	201	0.01	305	0.013	1012	0.012					2577	0.303
	2088	0.092		1222	0.076	1593	0.076	1744	0.075	6647	0.08					2991	0.352
	298	0.013		298	0.019	240	0.011	316	0.014	1152	0.014					3209	0.378
	0	0		21	0.001	0	0	23	0.001	44	0.001					3625	0.426
	1073	0.047		1170	0.073	951	0.045	1437	0.062	4631	0.056					3976	0.468
	1031	0.046		548	0.034	1110	0.053	429	0.018	3118	0.038					4359	0.513
	280	0.012		280	0.017	389	0.018	443	0.019	1392	0.017					4895	0.576
	84	0.004		247	0.015	237	0.011	94	0.004	662	0.008					5199	0.612
	590	0.026		581	0.036	634	0.03	661	0.028	2466	0.03					5981	0.704
Total:	43	0.002		263	0.016	0	0	263	0.011	569	0.007					6155	0.724
	271	0.012		271	0.017	204	0.01	354	0.015	1100	0.013					7232	0.851
	1071	0.047		392	0.024	598	0.028	957	0.041	3018	0.036					7250	0.853
	88	0.004		88	0.005	125	0.006	125	0.005	426	0.005					8400	0.993
	782	0.035		1134	0.071	938	0.045	538	0.023	3392	0.041						
	603	0.027		603	0.038	608	0.029	714	0.031	2528	0.03						
	3400	0.15		330	0.021	1354	0.064	577	0.025	5661	0.068						
	86	0.004		86	0.005	1158	0.055	1158	0.05	2488	0.03						
	184	0.008		184	0.011	412	0.02	412	0.018	1192	0.014						
	2	0		0	0	0	0	0	0	2	0						
	171	0.008		171	0.011	171	0.008	171	0.007	684	0.008						
	1670	0.074		644	0.04	2597	0.123	3146	0.135	8057	0.097						
	22597	1	1	16040	1	21037	1	23309	1	82983	1						



3 March - 20 September 1993

Figure B-5: LSD 46 Individual MPE Operating Profiles



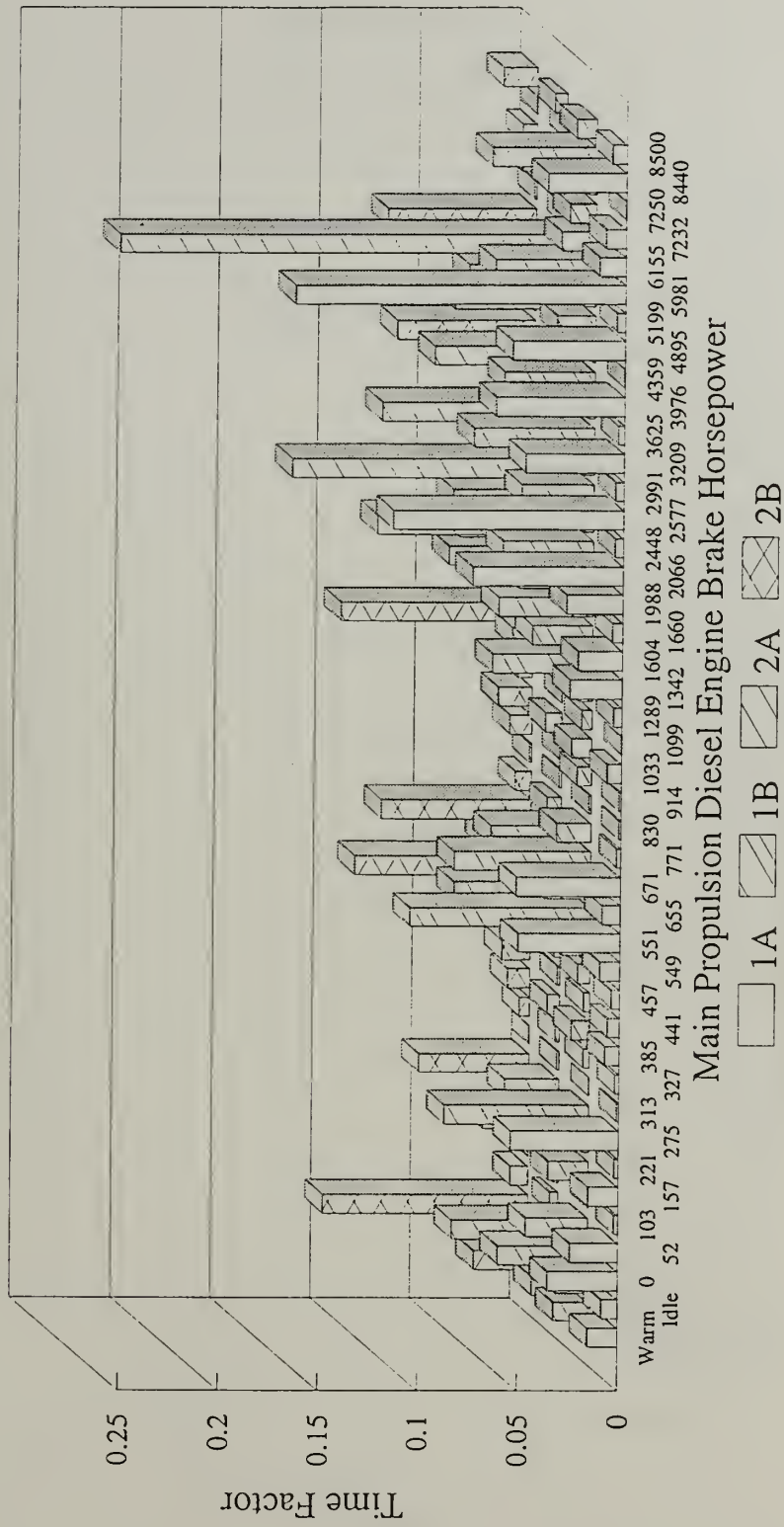
3 March - 20 September 1993

Figure B-6: LSD 46 Composite Operating Profile

B.4: USS RUSHMORE (LSD 47)

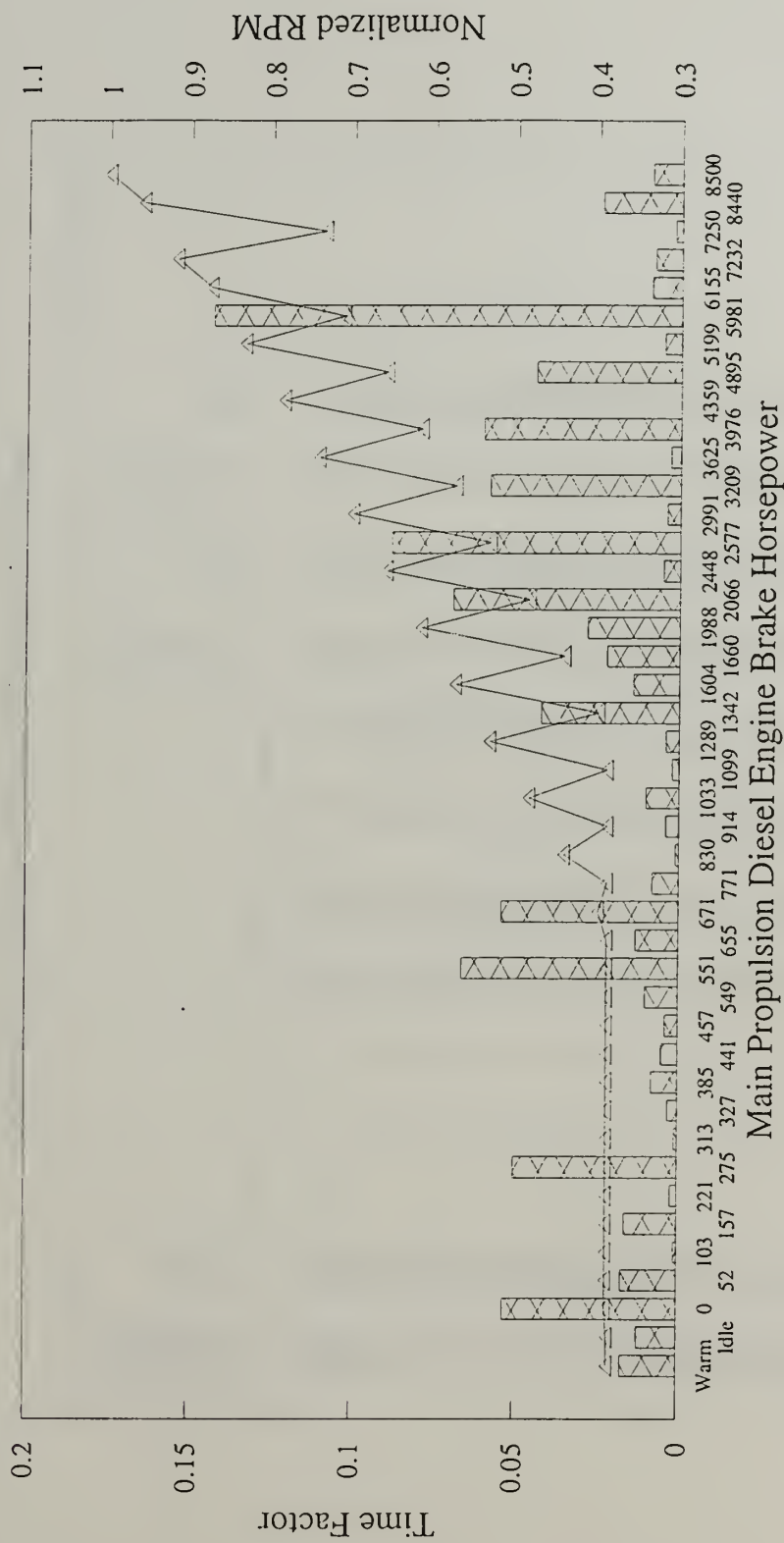
Table B-5: USS RUSHMORE (LSD 47) MPE Data Summary

MPE Time Factor Calculations	1A	1A_n	1B	1B_n	2A	2A_n	2B	2B_n	Total	Total_n	Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n
Data Points:	764		791		730		728		3013						385	0
Total Time:	41529		34868		40651		28469		145517						385	0
Time Secured:	12201		12768		11610		14416		51095						387	0
Time Running:	29328	1	22100	1	29041	1	14023	1	94492	1					387	52
Time Warming Up:	441	0.015	380	0.017	368	0.013	362	0.027	1571	0.017					387	103
Time at Idle:	237	0.008	353	0.016	272	0.009	293	0.021	1571	0.017					387	157
Time at Power:	28650	0.977	21367	0.967	28401	0.978	13348	0.952	91766	0.971					387	221
															387	275
															387	313
															387	327
															387	365
															387	441
															387	457
															387	549
															387	551
															387	655
															387	671
															387	771
															387	830
															387	914
															387	1033
															387	1099
															387	1289
															387	1342
															387	1604
															387	1660
															387	1680
															387	1988
															387	2066
															387	2448
															387	2577
															387	2991
															387	3209
															387	3625
															387	3976
															387	4359
															387	4895
															387	5199
															387	5981
															387	6155
															387	7252
															387	7550
															387	8440
															387	8500
Total:	29328	1	22100	1	29041	1	14023	1	94492	1					1	1



1 June - 16 December 93

Figure B-7: LSD 47 Individual MPE Operating Profiles



Main Propulsion Diesel Engine Brake Horsepower

1 June - 16 December 93

Figure B-8: LSD 47 Composite Operating Profile

Table B-6: MPE Time Factor Summary by Coast

Total	Total_n	Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n	East	East_n	West	West_n	MPE Time Factor by Coast
		Engines/Shaft	Speed	RPM	RPM_n	Power	Power_n					
						Warm						
						Idle						
6227	0.014			200	0.385		0	3198	0.02	3029	0.011	
8123	0.019			200	0.385		0	4082	0.025	4041	0.015	
20682	0.048	All Stop	0	0	0.387		0	11906	0.074	8776	0.032	
5270	0.012		2	2	0.387		52	2191	0.014	3079	0.011	
303	0.001		1	2	0.387		103	127	0.001	176	0.001	
3331	0.008		2	3	0.387		157	1012	0.006	2319	0.009	
1286	0.003		2	4	0.387		221	932	0.006	354	0.001	
14124	0.033		2	5	0.387		275	6490	0.04	7634	0.028	
439	0.001		1	3	0.387		313	155	0.001	284	0.001	
1332	0.003		2	6	0.387		327	310	0.002	1022	0.004	
2317	0.005		2	7	0.387		385	1243	0.008	1074	0.004	
1020	0.002		1	4	0.387		441	606	0.002	606	0.002	
1759	0.004		2	8	0.387		457	472	0.003	1287	0.005	
1142	0.003		2	9	0.387		549	188	0.001	954	0.004	
44177	0.102		1	5	0.387		551	9451	0.059	34726	0.128	
2113	0.005		1	6	0.387		655	800	0.005	1313	0.005	
24171	0.056		2	10	0.398		671	10051	0.062	14120	0.052	
7567	0.017		1	7	0.387		771	4148	0.026	3419	0.013	
708	0.002		2	11	0.387		830	204	0.001	504	0.002	
6285	0.014		1	8	0.387		914	1266	0.008	5019	0.018	
5026	0.012		2	12	0.483		1033	3230	0.02	1796	0.007	
939	0.002		1	9	0.387		1099	442	0.003	497	0.002	
4427	0.01		2	13	0.387		1289	2662	0.016	1765	0.006	
36217	0.083		1	10	0.398		1342	12497	0.077	23720	0.087	
4385	0.01		2	14	0.573		1604	1536	0.01	2849	0.01	
6575	0.015		1	11	0.44		1660	162	0.001	6413	0.024	
13416	0.031		2	15	0.615		1988	234	0.023	7787	0.048	
12288	0.028		1	12	0.483		2066	3563	0.022	8725	0.032	
6439	0.015		2	16	0.658		2448	3546	0.022	2893	0.011	
10983	0.025		1	13	0.376		2577	907	0.006	10076	0.037	
6401	0.015		2	17	0.531		2991	3310	0.02	3091	0.011	
12101	0.028		1	14	0.573		3209	3378	0.009	10654	0.039	
4800	0.011		2	18	0.742		3625	3056	0.019	1744	0.006	
24682	0.057		1	15	0.615		3976	8105	0.05	16577	0.061	
7270	0.017		2	19	0.785		4359	6474	0.04	796	0.003	
17610	0.041		1	16	0.658		4895	4429	0.027	13181	0.048	
14640	0.034		2	20	0.833		5199	612	0.075	2482	0.009	
45576	0.105		1	17	0.712		5981	10951	0.068	34625	0.127	
6448	0.015		2	21	0.875		6155	2904	0.018	3544	0.013	
11524	0.027		2	22	0.917		7232	851	0.024	7692	0.028	
6342	0.015		1	18	0.735		7250	853	0.006	5331	0.02	
8066	0.019		2	23	0.958		8440	832	0.005	7234	0.027	
15234	0.035		2	24	1		8500	8057	0.05	7177	0.026	
433765	1							161538	1	272227	1	Total

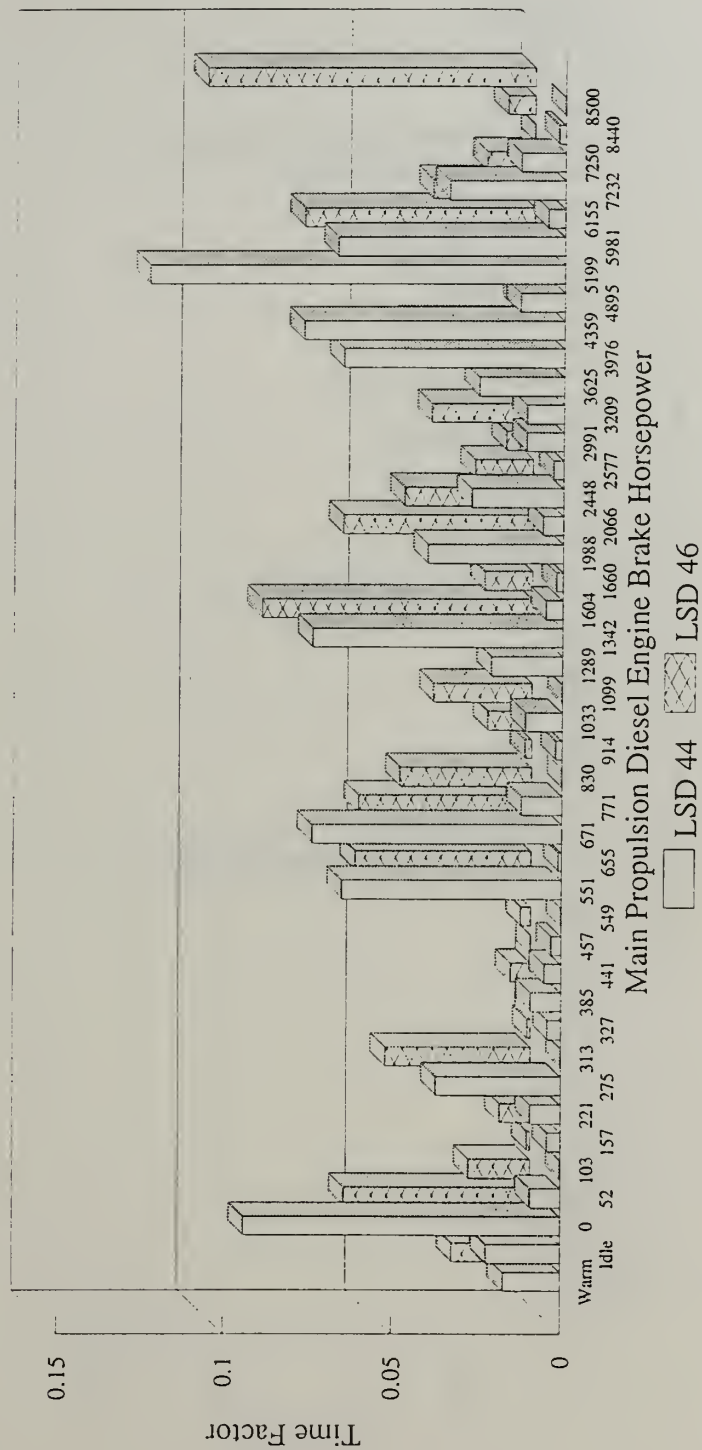


Figure B-9: East Coast Ship MPE Operating Profiles

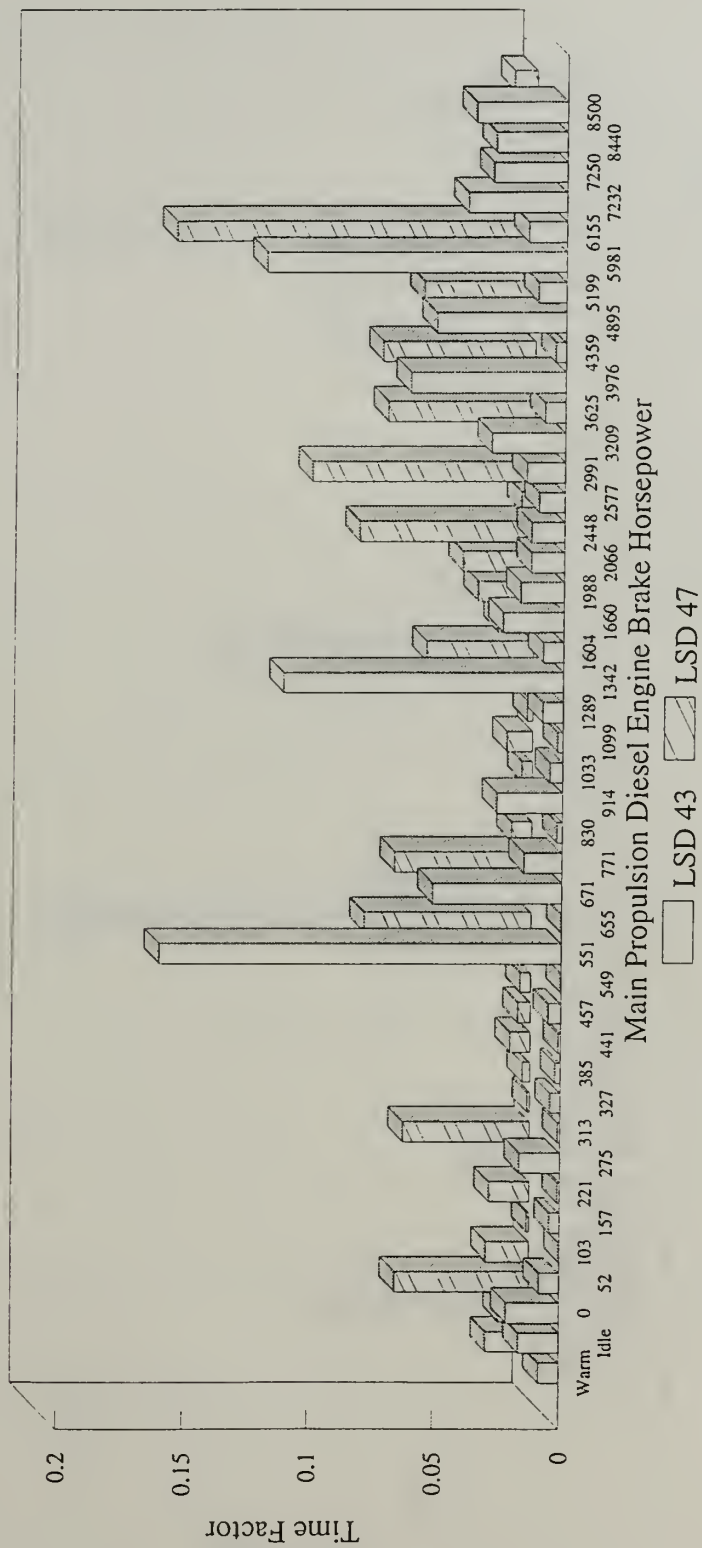


Figure B-10: West Coast Ship MPE Operating Profiles

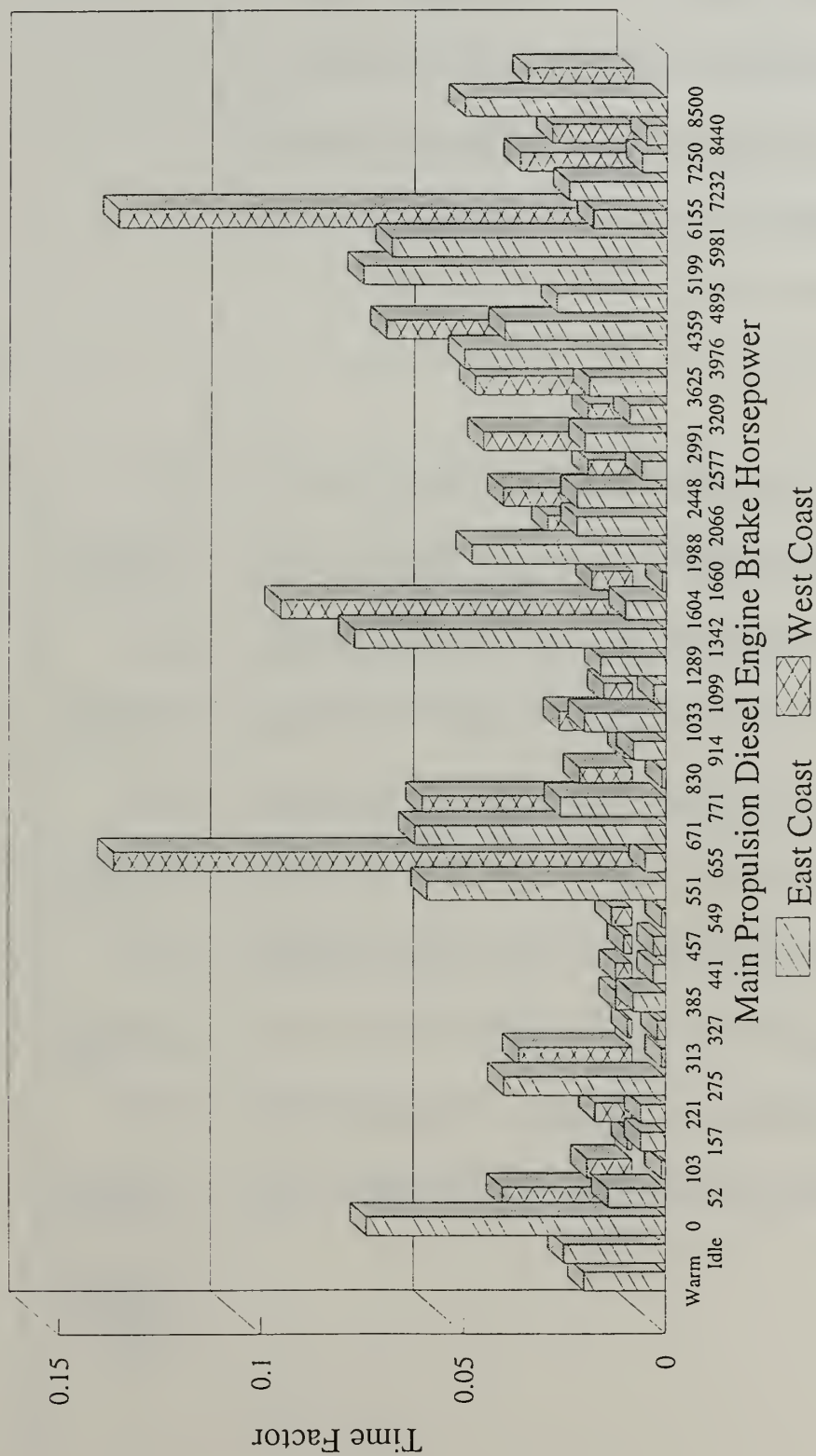


Figure B-11: East versus West Coast Ship MPE Operating Profiles

Table B-7: LSD 41 Class MPE Composite Summary

MPE Time Factor Calculations															
LSD 43	LSD 43_n	LSD 44	LSD 44_n	LSD 46	LSD 46_n	LSD 47	LSD 47_n	Total	Total_n	Engines/Shift	Speed	RPM	RPM_n	Power	Power_n
Data Points:	5011	2816		4267		3013		15107						Warm	0
Total Time:	252324	133052		159845		145517		690738						Idle	0
Time Secured:	74589	54499		76872		51025		256985							0
Time Running:	177735	78553	1	82973	1	94492	1	433753	1						52
Time Warming Up:	1458	1306	0.017	1892	0.023	1571	0.017	6227	0.014						103
Time at Idle:	2886	1725	0.022	2357	0.028	1155	0.012	8123	0.019						157
Time at Power:	173391	75522	0.961	78724	0.949	91766	0.971	419403	0.967						221
															275
															313
															327
															385
															441
															457
															549
															551
															655
															671
															771
															830
															914
															1033
															1099
															1289
															1529
															1580
															1604
															1660
															1988
															2324
															2430
															2488
															2577
															2991
															3032
															3209
															3426
															3976
															4680
															5130
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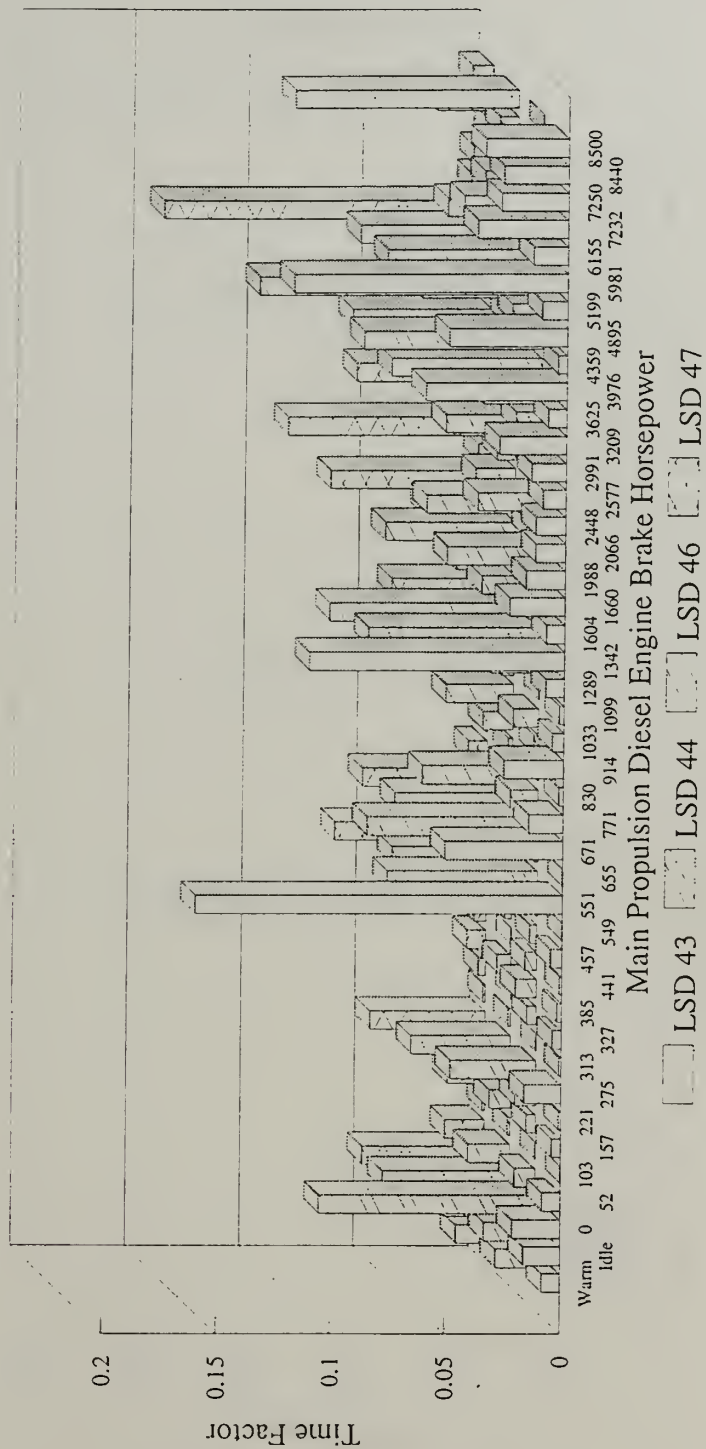


Figure B-12: Individual Ship MPE Operating Profiles

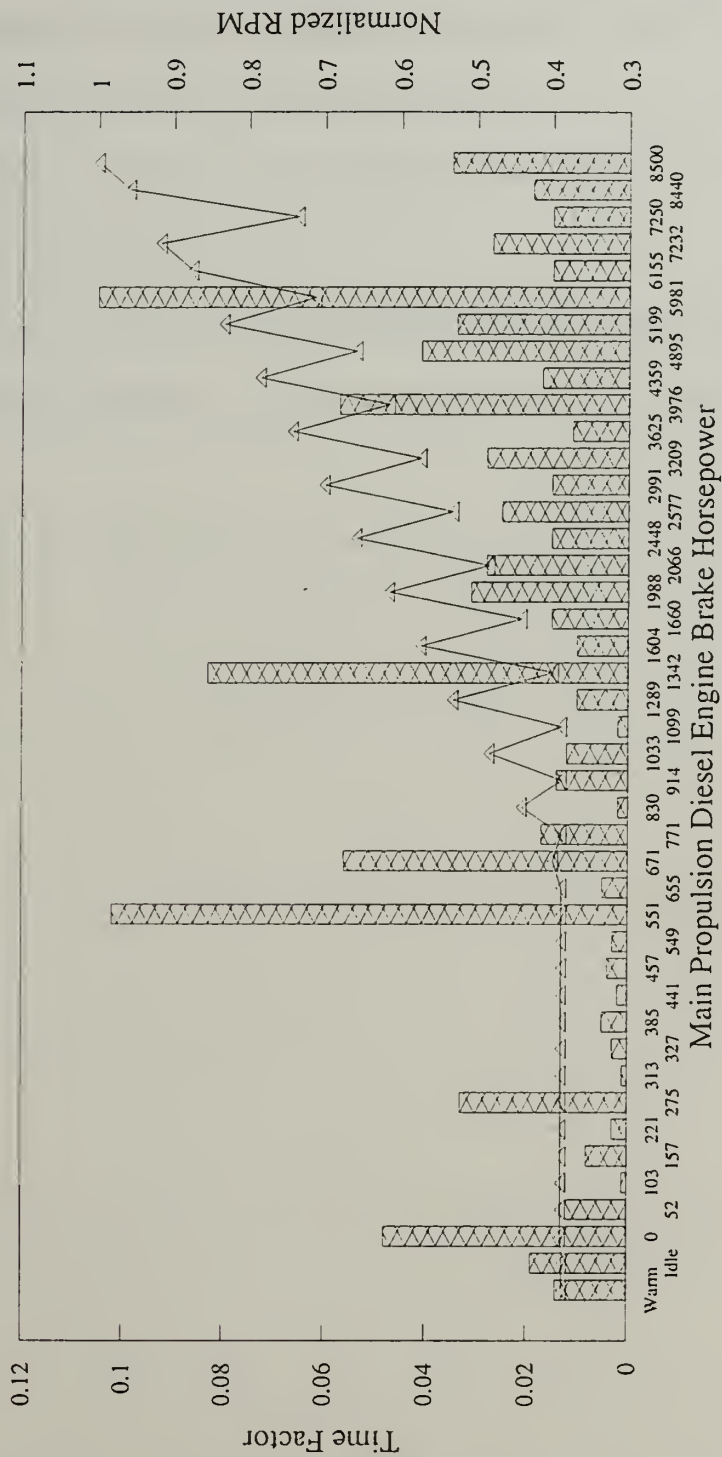


Figure B-13: LSD 41 Class Composite Ship Operating Profile

Appendix C: MPE Emission Prediction Data

This appendix provides the data used to make engine duty cycle emission predictions made in Chapter 4. Section C-1 data for the Colt-Pielstick PC4-2B formed the basis for emission contour plots derived from *The Motor Ship* article of August 1992. "_n" in this section indicate Power Fraction and RPM Factor from equations 16 and 17.

Section C-2 gives duty cycle emission prediction spreadsheet pages based on linear interpolation of emission contour maps provided as Section C-3.

NOx	g/kWh	RPM	Power d	Power	g/bhp-h	NOx Level	RPM	Power	RPM, n	Power, n	CO	CO Level	RPM	Power	RPM, n	Power, n
10	3.38	407	7.457	1274	1.035	1.075	1.1	3.5	3.5	4.1	0.82027	415	1215	1.075	1.075	1.025
10	3.38	421	7.457	1185	1.185	0.93	1.1	3.35	3.35	4.1	0.82027	408	1185	1.03	1.03	1
10	3.8	433	7.457	1102	1.185	0.89	1.1	3.31	3.31	3.9	0.82027	403	1156	1.015	1.015	0.975
10	3.91	440	7.457	1055	1.2	0.89	1.1	3.3	3.3	3.85	0.82027	402	1141	1.01	1.01	0.963
10	4.11	452	7.457	966	1.26	0.815	1.1	3.3	3.3	3.5	0.82027	402	1037	1.01	1.01	0.875
10	4.37	468	7.457	836	1.34	0.7	1.1	3.4	3.4	3.1	0.82027	409	919	1.045	1.045	0.775
16	0	200	11.9312	462	0	0.39	1.1	3.45	3.45	3	0.82027	412	889	1.06	1.06	0.75
16	0.26	220	11.9312	385	0.1	0.325	1.1	3.6	3.6	2.83	0.82027	421	839	1.105	1.105	0.708
16	0.9	255	11.9312	296	0.275	0.25	1.1	3.8	3.8	2.76	0.82027	433	818	1.165	1.165	0.69
16	1.2	274	11.9312	267	0.37	0.225	1.1	3.9	3.9	2.8	0.82027	439	830	1.195	1.195	0.7
16	1.6	298	11.9312	258	0.49	0.218	1.1	3.96	3.96	3	0.82027	443	889	1.215	1.215	0.75
16	1.9	317	11.9312	267	0.585	0.225	1.1	3.93	3.93	3.3	0.82027	441	978	1.205	1.205	0.825
16	2.06	326	11.9312	296	0.63	0.25	1.1	3.91	3.91	3.5	0.82027	440	1037	1.2	1.2	0.875
16	2.2	335	11.9312	326	0.675	0.275	1.1	3.8	3.8	3.96	0.82027	433	1173	1.165	1.165	0.99
16	2.28	340	11.9312	385	0.7	0.325	1.1	3.79	3.79	4	0.82027	433	1185	1.165	1.165	1
16	2.3	341	11.9312	415	0.705	0.35	1.1	3.6	3.6	4.09	0.82027	421	1212	1.105	1.105	1.023
16	2.3	341	11.9312	444	0.705	0.375	1.1	3.5	3.5	4.1	0.82027	415	1215	1.075	1.075	1.025
16	2.25	338	11.9312	504	0.69	0.425	1.2	3	3	4.4	0.89484	384	1304	0.92	0.92	1.1
16	2.1	329	11.9312	581	0.645	0.49	1.2	2.91	2.91	3.92	0.89484	379	1161	0.895	0.895	0.98
16	1.9	317	11.9312	652	0.585	0.55	1.2	2.9	2.9	3.65	0.89484	378	1081	0.89	0.89	0.913
16	1.47	290	11.9312	741	0.45	0.625	1.2	3.1	3.1	3.1	0.89484	384	919	0.92	0.92	0.775
16	1.14	270	11.9312	794	0.35	0.67	1.2	3.1	3.1	2.7	0.89484	390	800	0.95	0.95	0.675
12	-0.5	169	8.9484	237	-0.155	0.2	1.2	3.2	3.2	2.5	0.89484	396	741	0.98	0.98	0.625
12	0.4	225	8.9484	148	0.125	0.125	1.2	3.25	3.25	2.4	0.89484	399	711	0.995	0.995	0.6
12	0.6	237	8.9484	124	0.185	0.105	1.2	3.4	3.4	2.3	0.89484	409	681	1.045	1.045	0.575
12	1.1	267	8.9484	95	0.335	0.08	1.2	3.5	3.5	2.3	0.89484	415	681	1.075	1.075	0.575
12	1.6	298	8.9484	62	0.49	0.053	1.2	3.6	3.6	2.31	0.89484	421	684	1.105	1.105	0.578
12	2.1	329	8.9484	50	0.645	0.043	1.2	3.9	3.9	2.45	0.89484	439	726	1.195	1.195	0.613
12	2.5	353	8.9484	39	0.765	0.033	1.4	1.16	1.16	1	1.04398	271	296	0.355	0.355	0.25
12	2.6	360	8.9484	41	0.8	0.035	1.4	1.15	1.15	0.95	1.04398	271	281	0.355	0.355	0.238
12	3.1	390	8.9484	59	0.95	0.05	1.4	1.3	1.3	0.9	1.04398	280	267	0.4	0.4	0.225
12	3.6	421	8.9484	107	1.105	0.09	1.4	1.6	1.6	0.9	1.04398	298	267	0.49	0.49	0.225
12	3.9	439	8.9484	148	1.195	0.125	1.4	2.6	2.6	0.92	1.04398	360	273	0.8	0.8	0.23
12	4.1	452	8.9484	276	1.26	0.233	1.4	2.7	2.7	0.94	1.04398	360	273	0.83	0.83	0.235
12	4.2	458	8.9484	356	1.29	0.3	1.4	2.75	2.75	1	1.04398	369	296	0.845	0.845	0.25
12	4.2	458	8.9484	504	1.29	0.425	1.4	2.7	2.7	1.06	1.04398	366	314	0.83	0.83	0.265
12	4.1	432	8.9484	593	1.26	0.5	1.4	2.6	2.6	1.1	1.04398	360	326	0.8	0.8	0.275
12	3.6	421	8.9484	770	1.165	0.65	1.4	2.1	2.1	1.12	1.04398	329	332	0.645	0.645	0.28
12	3.5	390	8.9484	859	1.105	0.725	1.4	1.8	1.8	1.1	1.04398	310	326	0.55	0.55	0.275
12	3.1	335	8.9484	993	0.95	0.838	1.4	1.6	1.6	1.08	1.04398	298	320	0.49	0.49	0.27
12	2.8	372	8.9484	1067	0.86	0.9	1.4	1.5	1.5	1.05	1.04398	292	311	0.46	0.46	0.263
12	2.61	360	8.9484	1102	0.8	0.93	1.4	1.4	1.4	1.03	1.04398	280	305	0.4	0.4	0.258
12	1.96	320	8.9484	1197	0.6	1.01	1.4	1.16	1.16	1	1.04398	271	296	0.355	0.355	0.25
12	1.3	280	8.9484	1280	0.4	1.08	1.4	1.1	1.1	0.4	1.1855	206	119	0.03	0.03	0.1
14	-0.33	180	10.4398	385	-0.1	0.325	1.5	0.1	0.1	0.5	1.1855	221	148	0.105	0.105	0.125
14	0.33	220	10.4398	296	0.1	0.25	1.5	0.6	0.6	0.57	1.1855	237	169	0.185	0.185	0.143
14	0.8	249	10.4398	237	0.245	0.2	1.5	0.8	0.8	0.6	1.1855	249	178	0.245	0.245	0.15
14	1.1	267	10.4398	207	0.395	0.175	1.5	1.1	1.1	0.65	1.1855	267	193	0.335	0.335	0.163
14	1.6	298	10.4398	172	0.49	0.145	1.5	1.6	1.6	0.7	1.1855	298	207	0.49	0.49	0.175
14	2.1	329	10.4398	148	0.645	0.125	1.5	2.1	2.1	0.7	1.1855	329	207	0.645	0.645	0.175
14	2.6	360	10.4398	160	0.8	0.135	1.5	2.4	2.4	0.71	1.1855	347	210	0.735	0.735	0.178
14	2.9	378	10.4398	184	0.89	0.155	1.5	2.5	2.5	0.73	1.1855	353	216	0.765	0.765	0.183
14	3.1	390	10.4398	213	0.95	0.18	1.5	2.6	2.6	0.75	1.1855	360	222	0.8	0.8	0.188
14	3.35	406	10.4398	296	1.03	0.25	1.5	2.8	2.8	0.82	1.1855	372	243	0.86	0.86	0.205
14	3.43	410	10.4398	356	1.05	0.3	1.5	2.94	2.94	0.9	1.1855	380	267	0.9	0.9	0.225

14	3.48	1.4	10.4398	413	415	1.065	0.35		15	3.05	1	1.1855	387	296	0.935	0.25
14	3.5	1.5	10.4398	415	444	1.075	0.375		15	3.08	1.05	1.1855	389	311	0.945	0.263
14	3.4	1.85	10.4398	409	548	1.045	0.463		15	2.8	1.18	1.1855	384	350	0.92	0.295
14	3.2	2.2	10.4398	396	652	0.98	0.55		15	2.8	1.2	1.1855	372	356	0.86	0.3
14	2.9	2.5	10.4398	378	741	0.89	0.63		15	1.6	1.12	1.1855	298	356	0.49	0.3
14	2.6	2.73	10.4398	360	809	0.8	0.683		15	1.3	1.12	1.1855	280	332	0.4	0.28
14	2.6	3	10.4398	335	889	0.675	0.75		15	0.98	1.08	1.1855	260	320	0.3	0.27
14	1.79	3.2	10.4398	310	948	0.55	0.8		15	0.65	1.04	1.1855	240	308	0.2	0.26
14	1.3	3.4	10.4398	280	1007	0.4	0.85		15	0	0.88	1.1855	200	261	0	0.22
									15	-0.65	0.72	1.1855	160	213	-0.2	0.18
									15	2.28	4.2	1.1855	340	1244	0.7	1.05
									15	2.35	3.6	1.1855	344	1067	0.72	0.9
									15	2.41	3.2	1.1855	348	948	0.74	0.8
									15	2.5	2.8	1.1855	353	830	0.765	0.7
									15	2.6	2.4	1.1855	360	711	0.8	0.6
									15	2.7	2	1.1855	366	593	0.83	0.5
									15	2.93	1.5	1.1855	380	444	0.9	0.375
									15	3.1	1.32	1.1855	390	391	0.95	0.33
									15	3.35	1.22	1.1855	406	361	1.03	0.305
									15	3.6	1.3	1.1855	421	385	1.105	0.325
									15	3.9	1.4	1.1855	439	415	1.195	0.35
									2	0.95	0.32	1.4914	256	95	0.29	0.08
									2	1.1	0.35	1.4914	267	104	0.355	0.088
									2	1.4	0.45	1.4914	286	133	0.43	0.113
									2	1.6	0.49	1.4914	298	145	0.49	0.123
									2	1.7	0.5	1.4914	304	148	0.52	0.125
									2	2.1	0.5	1.4914	329	148	0.645	0.125
									2	2.3	0.5	1.4914	341	148	0.705	0.123
									2	2.4	0.52	1.4914	347	154	0.735	0.13
									2	2.6	0.54	1.4914	360	160	0.8	0.135
									2	2.9	0.6	1.4914	378	178	0.89	0.15
									2	3.3	0.7	1.4914	402	207	1.01	0.175
									2	3.6	0.8	1.4914	421	237	1.105	0.2
									2	3.9	0.92	1.4914	439	273	1.195	0.23
									2	-0.16	1.28	1.4914	190	379	-0.05	0.32
									2	0.65	1.23	1.4914	240	364	0.2	0.308
									2	1.3	1.21	1.4914	280	359	0.4	0.303
									2	1.8	1.27	1.4914	310	376	0.55	0.318
									2	2.1	1.3	1.4914	329	385	0.645	0.325
									2	2.3	1.32	1.4914	341	391	0.705	0.33
									2	2.5	1.42	1.4914	353	421	0.765	0.355
									2	2.6	1.55	1.4914	360	459	0.8	0.388
									2	2.63	1.7	1.4914	361	504	0.805	0.425
									2	2.6	1.8	1.4914	360	533	0.8	0.45
									2	2.55	2	1.4914	356	593	0.78	0.5
									2	2.4	2.4	1.4914	347	711	0.735	0.6
									2	2.28	2.8	1.4914	340	830	0.7	0.7
									2	2.11	3.2	1.4914	329	948	0.845	0.8
									2	1.96	3.6	1.4914	320	1067	0.6	0.9
									2	1.63	4.4	1.4914	300	1304	0.5	1.1
									2.5	0	1.5	1.86425	200	444	0	0.375
									2.5	0.65	1.4	1.86425	240	415	0.2	0.35
									2.5	1.3	1.36	1.86425	280	403	0.4	0.34
									2.5	1.8	1.36	1.86425	310	403	0.55	0.34
									2.5	2.1	1.4	1.86425	329	415	0.645	0.35
									2.5	2.25	1.5	1.86425	338	444	0.69	0.375
									2.5	2.3	1.6	1.86425	341	474	0.705	0.4
									2.5	2.32	1.7	1.86425	342	504	0.71	0.425
									2.5	2.3	1.78	1.86425	341	527	0.705	0.445
									2.5	2.2	1.9	1.86425	335	563	0.675	0.475
									2.5	1.96	2.1	1.86425	320	622	0.6	0.525
									2.5	0.96	2.72	1.86425	200	806	0.3	0.68

HC	g/kWh	RPM	Power	HC Level	RPM	Power	RPM, n	Power, n	CO2	g/kWh	RPM	Power	CO2 Level	g/kWh	RPM	Power	RPM, n	Power, n
0.4	-0.33	0.72	0.29828	180	213	-0.1	0.18	0.1075	585	3.25	399	4.3	436.2345	399	1274	0.995	1.075	1
0.4	0.3	0.85	0.29828	218	252	0.09	0.213	0.995	585	3.57	4	4.36	436.2345	419	1185	1.095	1	1
0.4	0.6	0.93	0.29828	237	276	0.185	0.233	0.99	585	3.6	396	3.96	436.2345	421	1173	1.105	0.99	0.89
0.4	0.8	1	0.29828	249	296	0.245	0.28	0.538	585	3.9	356	3.56	436.2345	439	1055	1.195	0.89	0.538
0.4	1.1	1.12	0.29828	267	332	0.335	0.34	0.645	585	1.8	2.15	2.15	436.2345	310	637	0.55	0.538	0.528
0.4	1.6	1.36	0.29828	298	403	0.49	0.34	0.8	585	2.1	2.11	2.11	436.2345	329	625	0.645	0.528	0.525
0.4	1.85	1.5	0.29828	313	444	0.565	0.375	0.958	585	2.6	2.1	2.1	436.2345	360	622	0.8	0.525	0.538
0.4	2.1	1.68	0.29828	329	498	0.645	0.42	1.058	585	3.1	2.15	2.15	436.2345	390	637	0.95	0.538	0.58
0.4	2.48	2	0.29828	352	593	0.76	0.5	1.155	585	3.6	2.32	2.32	436.2345	421	687	1.105	0.58	0.625
0.4	2.6	2.12	0.29828	360	628	0.8	0.53	1.195	585	3.77	2.5	2.5	436.2345	431	741	1.155	0.625	0.675
0.4	2.94	2.5	0.29828	380	741	0.9	0.625	1.253	585	3.9	2.7	2.7	436.2345	439	800	1.195	0.675	0.775
0.4	3.1	2.72	0.29828	390	806	0.95	0.68	1.273	575	2.1	3.1	3.1	428.7775	329	919	0.645	0.775	0.723
0.4	3.25	3	0.29828	399	889	0.995	0.75	1.293	575	2.35	3	2.89	428.7775	344	889	0.72	0.75	0.723
0.4	3.41	3.5	0.29828	409	1037	1.045	0.875	1.313	575	2.6	2.78	2.78	428.7775	360	856	0.8	0.895	0.695
0.4	3.51	4	0.29828	415	1185	1.075	1	1.333	575	2.9	3.1	3.1	428.7775	378	824	0.89	0.95	0.688
0.4	3.53	4.2	0.29828	417	1244	1.085	1.05	1.353	575	3.2	2.75	2.75	428.7775	390	815	0.95	0.98	0.688
0.5	-0.33	0.64	0.37285	180	190	-0.1	0.16	0.713	575	3.4	2.8	2.8	428.7775	402	824	1.01	0.695	0.7
0.5	0.3	0.76	0.37285	218	225	0.09	0.19	0.713	575	3.5	3.55	3.55	428.7775	415	844	1.075	0.713	0.713
0.5	0.6	0.85	0.37285	237	252	0.165	0.213	0.775	575	3.3	3.1	3.1	428.7775	418	889	1.09	0.75	0.775
0.5	1.1	1	0.37285	267	296	0.335	0.25	0.895	575	3.4	3.5	3.5	428.7775	415	939	1.075	0.793	0.775
0.5	1.6	1.15	0.37285	298	341	0.49	0.288	1.058	575	3.5	3.1	3.1	428.7775	418	919	1.09	0.75	0.775
0.5	2.1	1.32	0.37285	329	391	0.645	0.33	1.155	575	3.4	3.3	3.3	428.7775	409	939	1.075	0.793	0.775
0.5	2.5	1.5	0.37285	353	444	0.765	0.375	1.253	575	3.5	3.4	3.4	428.7775	415	939	1.075	0.793	0.775
0.5	3.1	1.8	0.37285	390	533	0.95	0.45	1.353	575	3.4	3.3	3.3	428.7775	409	978	1.045	0.825	0.825
0.5	3.42	2	0.37285	415	593	1.05	0.5	1.453	575	3.15	3.5	3.5	428.7775	393	1037	0.965	0.875	0.875
0.5	3.6	2.13	0.37285	421	631	1.105	0.533	1.553	575	2.9	3.6	3.6	428.7775	378	1067	0.89	0.89	0.9
0.5	3.8	2.3	0.37285	433	681	1.165	0.575	1.653	600	1.2	1.37	1.37	447.42	274	406	0.37	0.343	0.343
0.8	-0.33	0.36	0.59656	180	107	-0.1	0.09	0.343	600	1.6	1.38	1.38	447.42	298	409	0.49	0.345	0.345
0.8	0.3	0.45	0.59656	218	133	0.09	0.113	0.358	600	2.1	1.43	1.43	447.42	329	424	0.645	0.358	0.358
0.8	0.6	0.5	0.59656	237	148	0.185	0.125	0.37	600	2.6	1.48	1.48	447.42	360	439	0.8	0.37	0.37
0.8	1.1	0.58	0.59656	267	172	0.335	0.145	0.405	600	3.1	1.62	1.62	447.42	390	480	0.95	0.405	0.405
0.8	1.6	0.7	0.59656	298	207	0.49	0.175	0.445	600	3.6	1.78	1.78	447.42	421	527	1.105	0.445	0.445
0.8	2.1	0.8	0.59656	329	237	0.645	0.2	0.488	600	3.9	2	2	447.42	439	593	1.195	0.445	0.445
0.8	2.6	0.92	0.59656	360	273	0.8	0.23	0.528	635	-0.1	0.4	0.4	473.5195	194	119	-0.03	0.1	0.1
0.8	2.85	1	0.59656	375	296	0.875	0.25	0.538	635	0.1	0.42	0.42	473.5195	206	124	0.03	0.105	0.105
0.8	3.1	1.08	0.59656	390	320	0.95	0.27	0.553	635	0.6	0.45	0.45	473.5195	237	133	0.185	0.113	0.113
0.8	3.6	1.22	0.59656	421	361	1.105	0.305	0.588	635	1.1	0.51	0.51	473.5195	267	148	0.335	0.125	0.125
0.8	3.8	1.34	0.59656	433	397	1.165	0.335	0.613	635	1.6	0.58	0.58	473.5195	298	172	0.49	0.145	0.145
1	-0.33	0.28	0.7457	180	83	-0.1	0.07	0.16	635	2.1	0.64	0.64	473.5195	329	190	0.645	0.16	0.16
1	0.2	0.29	0.7457	212	86	0.06	0.073	0.18	635	2.6	0.72	0.72	473.5195	360	213	0.8	0.18	0.18
1	0.6	0.32	0.7457	237	95	0.185	0.08	0.213	635	3.1	0.85	0.85	473.5195	390	252	0.95	0.213	0.213
1	1.1	0.396	0.7457	267	117	0.335	0.099	0.253	635	3.6	1.01	1.01	473.5195	421	299	1.105	0.253	0.253
1	1.6	0.5	0.7457	298	148	0.49	0.125	0.288	635	3.9	1.15	1.15	473.5195	439	341	1.195	0.288	0.288
1	2.1	0.58	0.7457	329	172	0.645	0.145	0.313	800	1.1	0.11	0.11	596.56	267	33	0.335	0.028	0.028
1	2.6	0.68	0.7457	360	201	0.8	0.17	0.343	800	1.6	0.18	0.18	596.56	298	53	0.49	0.045	0.045
1	3.1	0.78	0.7457	390	231	0.95	0.195	0.368	800	2.1	0.2	0.2	596.56	329	59	0.645	0.05	0.05
1	3.6	0.9	0.7457	421	267	1.105	0.225	0.393	800	2.6	0.28	0.28	596.56	360	83	0.8	0.07	0.07
1	3.8	1	0.7457	433	296	1.165	0.25	0.418	800	3.1	0.35	0.35	596.56	390	104	0.95	0.088	0.088
2	2.3	0.32	1.4914	341	95	0.705	0.08	0.113	800	3.6	0.45	0.45	596.56	421	133	1.105	0.113	0.113
2	2.6	0.38	1.4914	360	113	0.8	0.095	0.125	800	3.9	0.6	0.6	596.56	439	178	1.195	0.15	0.15
2	3.1	0.42	1.4914	390	124	0.95	0.105	0.145	800	3.9	0.6	0.6	596.56	439	178	1.195	0.15	0.15
2	3.6	0.52	1.4914	421	154	1.105	0.13	0.165	800	3.9	0.6	0.6	596.56	439	178	1.195	0.15	0.15
2	3.8	0.6	1.4914	433	178	1.165	0.15	0.185	800	3.9	0.6	0.6	596.56	439	178	1.195	0.15	0.15

DUTY CYCLE COMPARISON												
Rated Speed	RPM Factor	Percent Load	Time Factor	NOx	NOx Time	CO	CO Time	HC	HC Time	CO2	CO2 Time	Japanese NOx Factor
ISO 8178-4 E3 Duty Cycle	0.630	0.250	0.150	11.9	1.785	1	0.15	0.52	0.078	462	69.3	2.304
	0.800	0.500	0.150	11.1	1.665	1.37	0.206	0.32	0.048	437	65.55	2.197
	0.910	0.750	0.500	9.7	4.85	0.91	0.455	0.27	0.135	422	211	7.139
	1.000	1.000	0.200	8	1.6	0.82	0.164	0.23	0.046	435	87	2.802
		Total	1	9.9	9.9		0.975		0.307		432.85	14.442
ISO 8178-4 E1 Duty Cycle	Idle	0	0.400	0.31	0.124	2	0.8	2	0.8	580	232	6.784
	0.400	0.250	0.250	12	3	1	0.25	0.42	0.105	460	115	4.207
	0.600	0.500	0.150	12	1.8	1.91	0.225	0.25	0.034	437	65.55	2.327
	0.800	0.750	0.140	10.6	1.484	1.6	0.224	0.15	0.021	430	2.172	0.841
	1.000	1.000	0.060	8	0.48	0.82	0.049	0.23	0.014	435	26.1	0.841
U.S. Navy Endurance Test		Total	1	6.888	6.888		1.61		0.974		498.85	16.331
	1.000	1.000	0.255	8	2.041	0.82	0.209	0.23	0.059	435	110.969	3.574
	1.000	0.850	0.128	8.6	1.097	0.81	0.103	0.28	0.036	429	54.719	1.787
	Idle	0.000	0.001	0.31	0.007	2	0.043	2	0.043	580	12.429	0.363
	1.000	1.000	0.234	8	1.869	0.82	0.192	0.23	0.054	435	101.648	3.274
ICOMIA 36-88 Duty Cycle	Idle	0.000	0.021	0.31	0.007	2	0.043	2	0.043	580	12.429	0.363
	0.750	0.500	0.064	11.2	0.72	1.6	0.103	0.3	0.019	437	28.093	0.954
	Idle	0.000	0.021	0.31	0.007	2	0.043	2	0.043	580	12.429	0.363
	1.000	0.850	0.021	8.6	0.184	0.81	0.017	0.28	0.006	429	9.193	0.3
	1.000	1.100	0.234	7.5	1.753	0.85	0.199	0.26	0.061	437	102.115	3.274
Japanese Heavy-Duty Diesel		Total	1	7.685	7.685		0.952		0.364		444.024	14.252
	Idle	0.000	0.400	0.31	0.124	2	0.8	2	0.8	580	232	6.784
	0.400	0.253	0.250	12	3	1	0.25	0.42	0.105	460	115	4.207
	0.600	0.465	0.150	12.1	1.815	2	0.3	0.25	0.038	439	65.85	2.327
	0.800	0.716	0.140	10.2	1.428	1.05	0.147	0.218	0.031	429	60.06	2.051
U.S. EPA 13-Mode Duty Cycle	1.000	1.000	0.060	8	0.48	0.82	0.049	0.23	0.014	435	26.1	0.841
		Total	1	6.847	6.847		1.546		0.988		499.01	16.21
	Idle	0.000	0.051	0.31	0.016	2	0.103	2	0.103	580	29.853	0.873
	0.400	1.000	0.104	9.5	0.992	1.65	0.172	0.8	0.084	429	44.793	1.757
	0.400	0.250	0.087	12	1.041	1	0.087	0.42	0.036	460	39.912	1.46
U.S. EPA 13-Mode Duty Cycle	0.600	1.000	0.157	9	1.416	1.3	0.205	0.1	0.016	433	68.134	2.441
	0.600	0.250	0.179	12	2.153	1	0.179	0.42	0.075	460	82.529	2.784
	0.800	0.750	0.421	10	4.206	1.05	0.442	0.225	0.095	425	178.75	6.161
		Total	1	9.824	9.824		1.188		0.409		443.971	15.476
	Idle	0.000	0.067	0.31	0.021	2	0.134	2	0.134	580	38.86	1.136
U.S. EPA 13-Mode Duty Cycle	0.200	0.020	0.080	2.1	0.168	1.7	0.136	1.7	0.136	597	47.76	1.546
	0.400	0.200	0.080	12	0.96	1	0.08	0.42	0.034	460	36.8	1.346
	0.600	0.500	0.080	12	0.96	1.91	0.153	0.225	0.018	437	34.96	1.241
	0.800	0.750	0.080	10	0.8	1.05	0.084	0.225	0.018	428	34.24	1.172
	1.000	1.000	0.080	8	0.64	0.82	0.066	0.23	0.018	435	34.8	1.121
U.S. EPA 13-Mode Duty Cycle	Idle	0.000	0.067	0.31	0.021	2	0.134	2	0.134	580	38.86	1.136
	1.000	1.000	0.080	8	0.64	0.82	0.066	0.23	0.018	435	34.8	1.121
	1.000	0.750	0.080	9.3	0.744	0.85	0.068	0.3	0.024	428	34.24	1.121
	1.000	0.500	0.080	10.5	0.84	0.99	0.079	0.39	0.031	440	35.2	1.121
	1.000	0.250	0.080	10.5	0.84	1.3	0.104	0.64	0.051	473	37.84	1.121
U.S. EPA 13-Mode Duty Cycle	1.000	0.020	0.080	8.5	0.68	3	0.24	3	0.24	615	49.2	1.121
	1.000	0.000	0.067	0.31	0.021	2	0.134	2	0.134	580	38.86	1.136
	Idle	0.000	0.067	0.31	0.021	2	0.134	2	0.134	580	38.86	1.136
		Total	1	7.335	7.335		1.478		0.99		496.42	15.439

CARB 8-Mode Duty Cycle	Idle	0	0	0.05	0.31	0.016	2	0.1	2	0.1	580	29	0.846
LSD Class 1 Engine/Shaft	Idle	1	1	0.15	10.5	1.575	0.99	0.149	0.39	0.059	428	66	2.101
	Max Torque	0	0	0.05	0.31	0.016	2	0.1	2	0.1	580	29	0.848
	Max Torque	0.85	1	0.15	8.5	1.275	0.95	0.143	0.21	0.032	432	64.8	2.171
	Max Torque	0.85	0.75	0.15	10	1.5	1	0.15	0.25	0.038	428	64.2	2.171
	Max Torque	0.85	0.5	0.15	10.9	1.655	1.09	0.164	0.35	0.053	437	65.55	2.171
	Max Torque	0.85	0.3	0.15	11.1	1.665	1.1	0.165	0.52	0.078	460	69	2.171
	Total	0.95	0.3	1	11.1	9.077	1.1	1.099	0.52	0.505	460	451.75	14.582
	0.387	0	0.012	0.001	0.9	0.001	1.8	0.002	1.8	0.002	579	0.579	0.017
	0.387	0	0.037	0.001	3.6	0.004	1.5	0.002	1.28	0.001	536	0.536	0.017
	0.387	0	0.052	0.002	4.7	0.009	1.4	0.003	1.13	0.002	527	1.054	0.034
LSD Class 2 Engine/Shaft	0.387	0	0.065	0.102	6	0.012	1.2	0.122	0.84	0.086	510	52.02	1.722
	0.387	0	0.077	0.005	6.5	0.033	1.1	0.006	0.7	0.004	502	2.51	0.085
	0.387	0	0.091	0.017	6.8	0.116	1.08	0.018	0.65	0.011	490	8.33	0.288
	0.387	0	0.108	0.014	7	0.098	1.07	0.015	0.6	0.008	473	6.622	0.237
	0.387	0	0.129	0.002	8	0.016	1.06	0.002	0.5	0.001	472	0.944	0.034
	0.398	0.018	0.158	0.083	8.9	0.739	1.04	0.086	0.45	0.037	470	39.01	1.398
	0.44	0.086	0.195	0.015	9.6	0.144	1.04	0.016	0.38	0.006	465	6.975	0.248
	0.483	0.157	0.243	0.028	10.5	0.294	1.1	0.031	0.27	0.008	460	12.88	0.454
	0.531	0.235	0.303	0.025	12	0.3	1.5	0.038	0.21	0.005	453	11.325	0.398
	0.573	0.303	0.378	0.028	13.4	0.375	2	0.056	0.18	0.005	446	12.488	0.438
LSD Class 2 Engine/Shaft	0.615	0.372	0.468	0.057	13.4	0.764	2.1	0.12	0.17	0.01	442	25.194	0.88
	0.658	0.442	0.576	0.041	12.1	1.496	2	0.082	0.16	0.007	436	17.876	0.625
	0.7	0.511	0.704	0.105	11.1	1.166	1.7	0.179	0.15	0.016	433	45.465	1.58
	0.735	0.568	0.853	0.015	10	0.15	1.5	0.024	0.15	0.002	429	6.435	0.224
	0.75	0.592	1	0	8.9	0	1.3	0	0.14	0	410	0	8.685
	Total	0.541	0.541	0.541	8.9	5.317	1.3	0.802	0.14	0.211	410	250.243	8.685
	0.387	0	0	0.081	0.31	0.025	2	0.162	2	0.162	580	46.98	1.372
	0.387	0.000	0.006	0.012	0.63	0.008	1.9	0.023	1.86	0.022	571	6.852	0.203
	0.387	0.000	0.018	0.008	1.1	0.009	1.8	0.014	1.71	0.014	563	4.504	0.136
	0.387	0.000	0.026	0.003	2	0.006	1.7	0.005	1.57	0.005	554	1.662	0.051
0.387	0.000	0.032	0.033	3.1	0.102	1.6	0.053	1.42	0.047	545	17.985	0.559	
0.387	0.000	0.038	0.003	3.5	0.011	1.5	0.005	1.28	0.004	536	1.608	0.051	
0.387	0.000	0.052	0.002	4.7	0.009	1.4	0.003	1.13	0.002	527	1.054	0.034	
0.387	0.000	0.054	0.004	4.9	0.02	1.3	0.005	0.99	0.004	519	2.076	0.068	
0.387	0.000	0.065	0.003	6	0.018	1.2	0.004	0.84	0.003	510	1.53	0.051	
0.398	0.018	0.079	0.056	6.5	0.364	1.2	0.067	0.7	0.039	500	28	0.943	
0.44	0.086	0.098	0.002	8	0.016	1.2	0.002	0.69	0.001	480	0.96	0.033	
0.483	0.157	0.122	0.012	8.9	0.107	1.2	0.014	0.65	0.008	473	5.676	0.194	
0.531	0.235	0.152	0.01	9.7	0.097	1.1	0.011	0.6	0.006	471	4.71	0.159	
0.573	0.303	0.189	0.01	10.4	0.104	1.05	0.011	0.55	0.006	466	4.66	0.157	
0.615	0.372	0.234	0.031	11.9	0.369	1	0.031	0.49	0.015	460	14.26	0.479	
0.658	0.442	0.288	0.015	12.3	0.185	1.1	0.017	0.44	0.007	451	6.765	0.229	
0.7	0.511	0.352	0.015	12.6	0.189	2	0.03	0.39	0.006	447	6.705	0.226	
0.742	0.579	0.426	0.011	12.3	0.135	2.1	0.023	0.3	0.003	442	4.862	0.164	
0.785	0.649	0.513	0.017	11.8	0.201	1.85	0.031	0.26	0.004	437	7.429	0.25	
0.833	0.728	0.612	0.034	10.8	0.367	1.5	0.031	0.24	0.008	433	14.722	0.494	
0.875	0.796	0.724	0.015	10.2	0.153	1.06	0.016	0.24	0.004	429	6.435	0.216	
0.917	0.865	0.851	0.027	9.1	0.246	0.94	0.025	0.23	0.006	428	11.556	0.385	
0.958	0.931	0.993	0.019	8.2	0.156	0.87	0.017	0.23	0.004	433	8.227	0.268	
1	1	1	0.035	8	0.28	0.82	0.029	0.23	0.008	435	15.225	0.49	
Total	0.458	0.458	0.458	8	3.177	0.82	0.649	0.23	0.388	435	224.443	7.212	21.897
Class Total	0.999	0.999	0.999	8.494	1.451	0.599	1.451	0.23	0.599	475	15.897	15.897	15.897

LSD Class Duty Cycle	Idle	0	0.000	0.083	0.31	0.026	2	0.166	2	0.166	580	48.14	1.408
		0	0.065	0.064	6	0.384	1.2	0.077	0.84	0.054	510	32.64	1.084
		0	0.032	0.128	3.1	0.397	1.6	0.205	1.42	0.182	545	69.76	2.169
		0.018	0.078	0.141	6.5	0.917	1.2	0.169	0.7	0.099	500	70.5	2.375
		0.018	0.078	0.141	8.9	0.685	1.04	0.08	0.45	0.035	470	36.19	1.297
		0.615	0.372	0.234	11.9	1.297	1	0.109	0.49	0.053	460	50.14	1.683
		0.615	0.372	0.468	13.4	0.683	2.1	0.107	0.17	0.009	442	22.542	0.787
		0.511	0.704	0.051	11.1	0.444	1.7	0.068	0.15	0.006	433	17.32	0.602
		0.700	0.352	0.160	12.6	2.016	2	0.32	0.39	0.062	447	71.52	2.407
		0.833	0.612	0.093	10.8	1.004	1.5	0.14	0.24	0.022	433	40.269	1.351
		1.000	1.000	0.054	8	0.432	0.82	0.044	0.23	0.012	435	23.49	0.756
			Total	1		8.285		1.485		0.7		483	15.919
T-AO 187 Class	Idle	0	0	0.083	0.31	0.026	2	0.166	2	0.166	580	48	1.408
		0.5	0	0.001	0.002	0.001	2	0.004	2	0.004	580	1	0.034
		0.5	0	0.011	0.3	0.003	1.9	0.021	1.9	0.021	580	6	0.187
		0.5	0	0.003	0.009	0.004	1.9	0.017	1.9	0.017	579	5	0.153
		0.5	0	0.004	0.007	0.5	0.004	1.8	0.013	0.013	579	4	0.119
		0.5	0	0.014	0.135	0.9	0.122	1.8	0.243	1.8	579	78	2.29
		0.5	0	0.028	0.008	3	0.024	1.7	0.014	1.57	554	4	0.136
		0.5	0	0.046	0.022	4.5	0.099	1.4	0.031	1.13	527	12	0.373
		0.5	0	0.069	0.018	6.2	0.112	1.2	0.022	0.84	510	9	0.305
		0.5	0	0.095	0.005	6.8	0.034	1.07	0.005	0.65	490	2	0.085
		0.516	0.032	0.126	0.139	8.5	1.182	1.06	0.147	0.55	472	66	2.344
		0.563	0.126	0.16	0.017	9.4	0.16	1.06	0.018	0.5	468	8	0.282
		0.615	0.23	0.181	0.04	10.3	0.412	1.04	0.042	0.45	464	19	0.651
		0.668	0.336	0.235	0.035	11.9	0.417	1.01	0.035	0.42	460	16	0.56
T-AO 187 Duty Cycle	Idle	0	0	0.083	0.31	0.026	2	0.166	2	0.166	580	48	1.408
		0.5	0	0.014	0.192	0.9	1.173	1.8	0.346	1.8	579	111	3.256
		0.516	0.032	0.126	8.5	1.853	1.06	0.231	0.55	0.12	472	103	3.675
		0.774	0.55	0.367	12.3	1.968	1.95	0.312	0.3	0.048	446	71	2.486
		0.876	0.76	0.558	11.1	3.252	1.5	0.44	0.27	0.079	435	127	4.443
		1	1	0.54	8	0.432	0.82	0.044	0.23	0.012	435	23	0.797
				0.917		7.704		1.539		0.771		483	14.657

DEMA Generator Duty Cycle	1	1	1	0.5	0.2	13.6	2.72	0.9	0.18	1	0.2	2.802
	1	1	1	0.75	0.4	15.3	6.12	0.7	0.28	0.83	0.332	5.604
	1	1	1	1	0.4	18.8	7.52	0.44	0.176	0.53	0.212	5.604
				Total	1		16.36		0.636		0.744	14.01
ISO 8178-4 D1 Duty Cycle	1	1	1	0.5	0.2	13.6	2.72	0.9	0.18	1	0.2	2.802
	1	1	1	0.75	0.5	15.3	7.65	0.7	0.35	0.83	0.415	7.005
	1	1	1	1	0.3	18.8	5.64	0.44	0.132	0.53	0.159	4.203
				Total	1		16.01		0.662		0.774	14.01
ISO 8178-4 D2 Duty Cycle	1	1	1	0.1	0.1	11.4	1.14	1.75	0.175	3.7	0.37	1.401
	1	1	1	0.25	0.3	12.5	3.75	1.35	0.405	1.35	0.405	4.203
	1	1	1	0.5	0.3	13.6	4.08	0.9	0.27	1	0.3	4.203
	1	1	1	0.75	0.25	15.3	3.825	0.7	0.175	0.83	0.208	3.502
	1	1	1	1	0.05	18.8	0.94	0.44	0.022	0.53	0.027	0.7
				Total	1		13.735		1.047		1.31	14.009
LSD Class SSDG Duty Cycle	1	1	1	0	0.033	10.5	0.347	1.95	0.064	5.7	0.188	0.462
	1	1	1	0.4	0.2	13	2.6	1.03	0.206	1.05	0.21	2.802
	1	1	1	0.5	0.464	13.6	6.31	0.9	0.418	1	0.464	6.5
	1	1	1	0.6	0.266	14.2	3.777	0.83	0.221	0.95	0.253	3.726
	1	1	1	0.8	0.026	15.7	0.408	0.65	0.017	0.8	0.021	0.364
	1	1	1	1	0.011	18.8	0.207	0.44	0.005	0.53	0.006	0.154
				Total	1		13.649		0.931		1.142	14.008
Summary (g/bhp-hr)			Japan NOx	CO	HC	CO2						
MPE												
ISO 8178-4 E3 Duty Cycle	9.9	14.4	14.4	1	0.3	433						
ISO 8178-4 E1 Duty Cycle	6.9	16.3	16.3	1.6	1	499						
U.S. Navy Endurance Test	7.7	14.3	14.3	1	0.4	444						
ICOMIA 36-88 Duty Cycle	6.8	16.2	16.2	1.5	1	499						
Japanese Heavy-Duty Diesel	9.8	15.5	15.5	1.2	0.4	444						
U.S. EPA 13-Mode Duty Cycle	7.3	15.4	15.4	1.5	1	496						
CARB 8-Mode Duty Cycle	9.1	14.6	14.6	1.1	0.5	452						
LSD Class Propeller Curve	8.5	15.9	15.9	1.5	0.6	475						
LSD Class Duty Cycle	8.3	15.9	15.9	1.5	0.7	483						
T-AO Class Propeller Curve	7.6	16.1	16.1	1.4	0.8	482						
T-AO Class Duty Cycle	7.7	14.7	14.7	1.5	0.8	483						
SSDG												
DEMA Generator Duty Cycle	16.4	14	14	0.6	0.7							
ISO 8178-4 D1 Duty Cycle	16	14	14	0.7	1							
ISO 8178-4 D2 Duty Cycle	13.7	14	14	1	1.3							
LSD Class SSDG Duty Cycle	13.6	14	14	0.9	1.1							

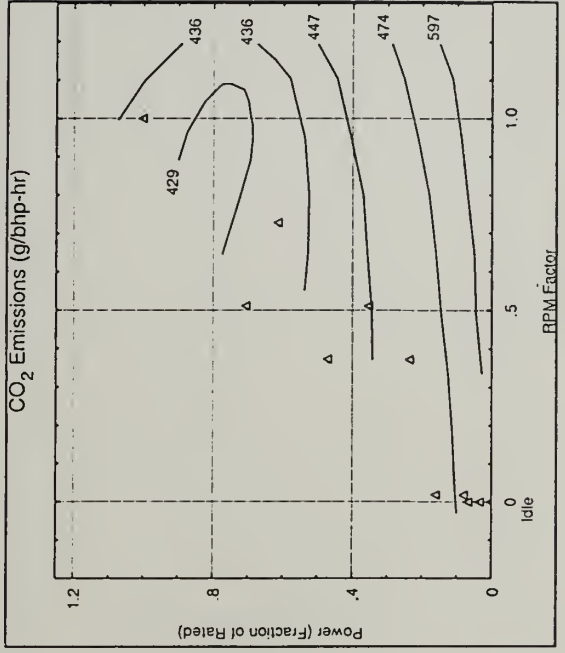
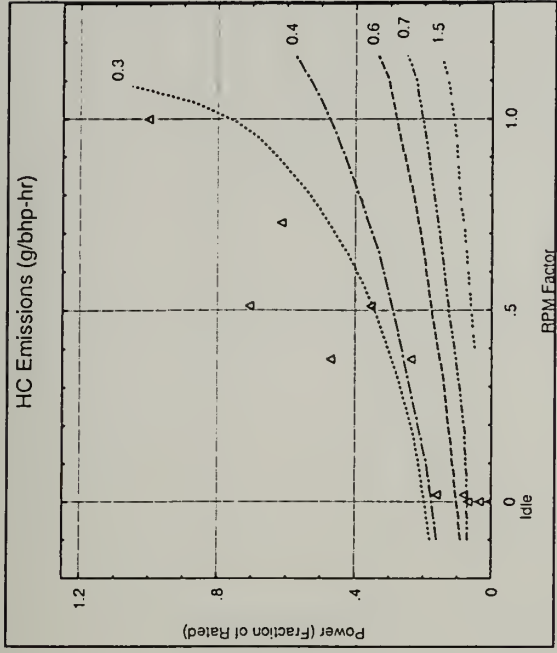
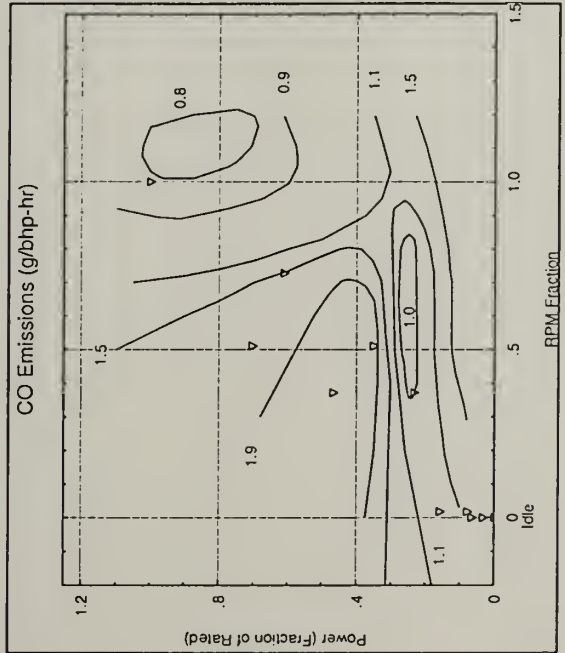
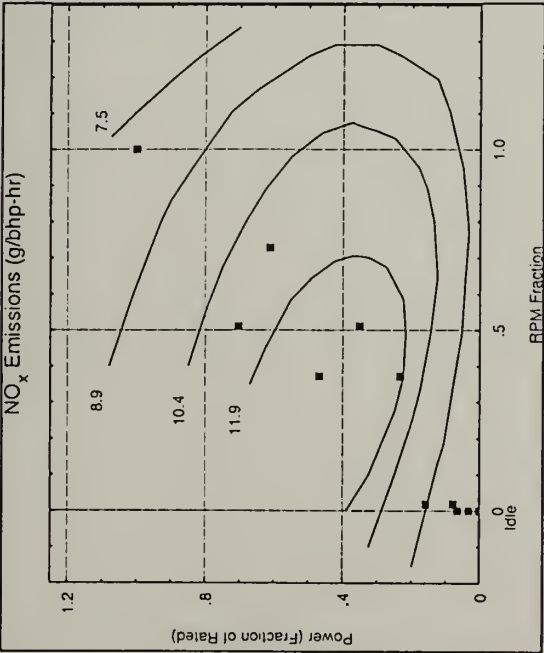


Figure C-1
LSD 41
Class
Duty Cycle
Emission
Contour
Plots

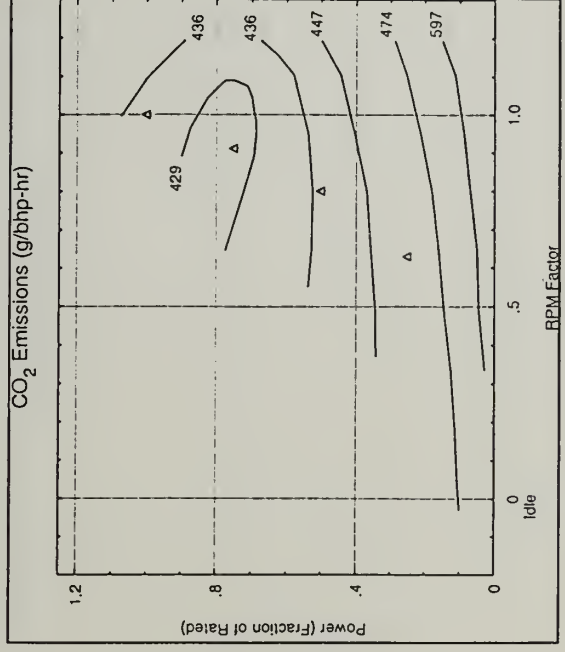
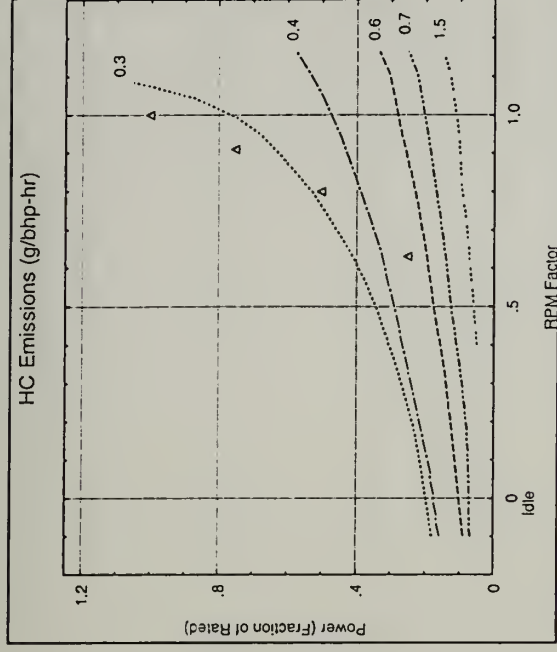
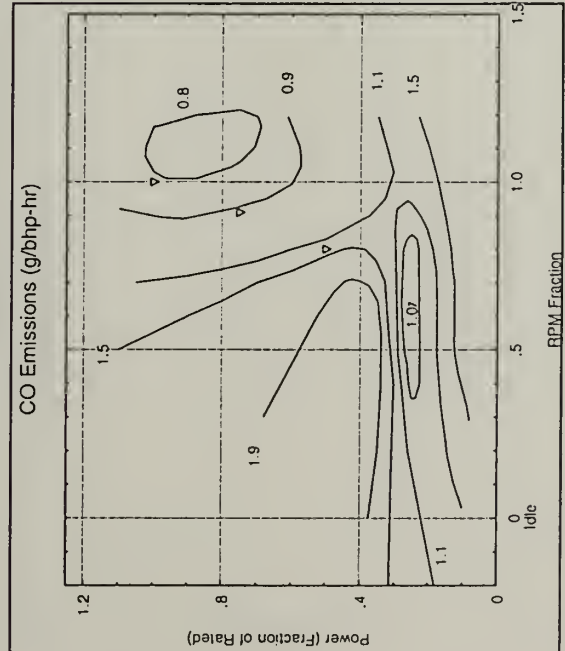
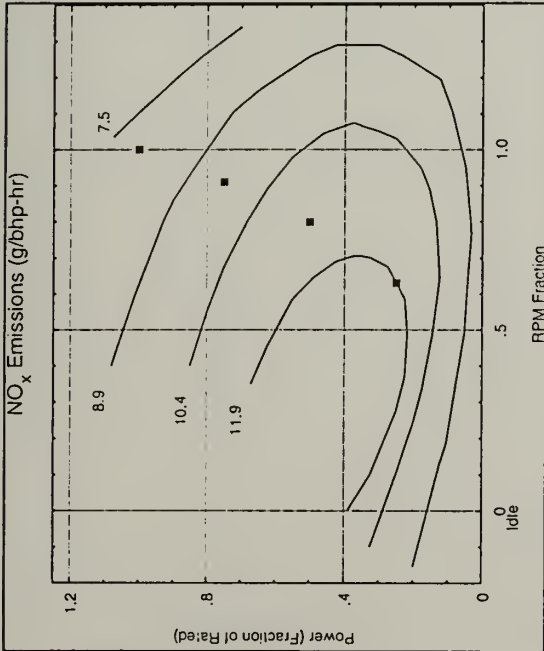


Figure C-2
ISO 8178-4
E3 Duty
Cycle
Emission
Contour
Plots

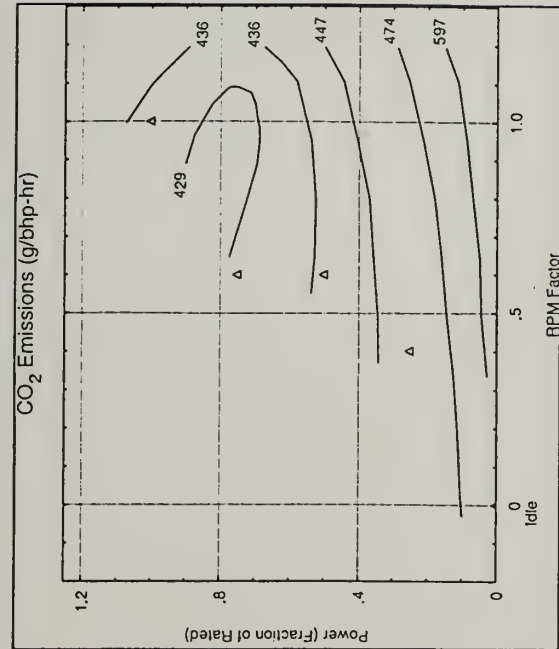
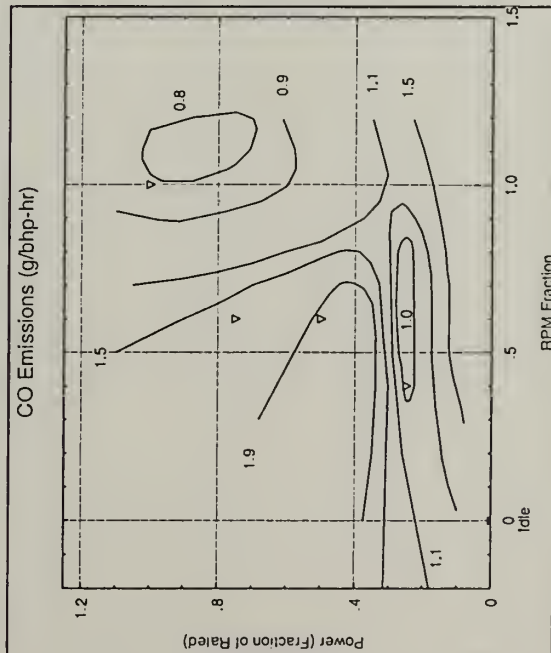
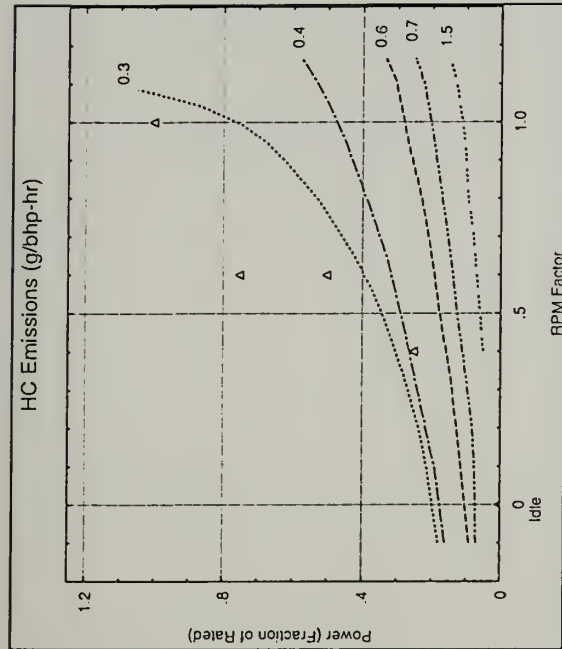
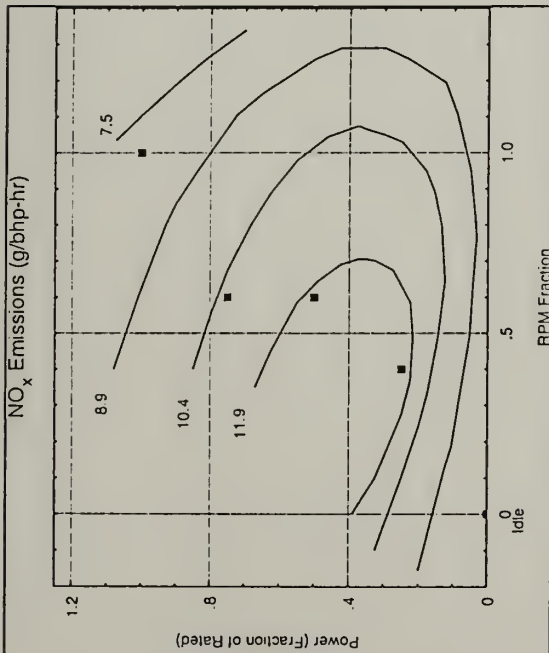


Figure C-3
ISO 8178-4
E1 Duty
Cycle
Emission
Contour
Plots

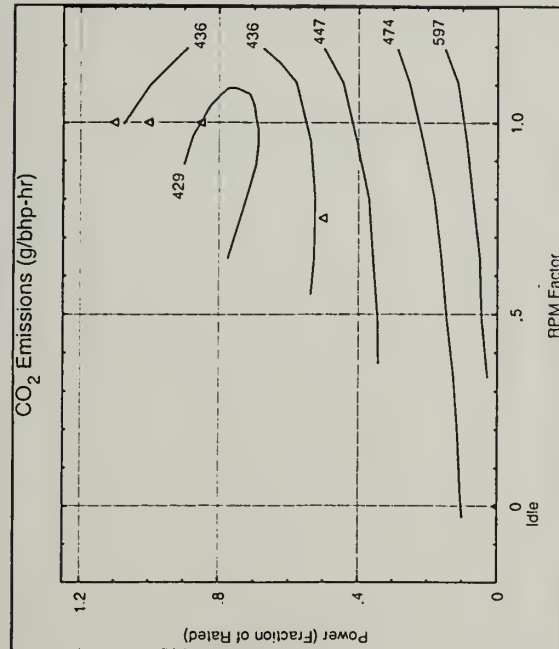
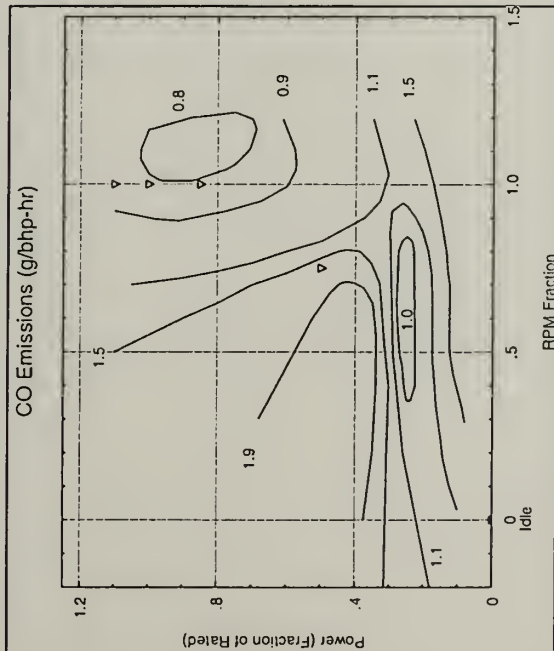
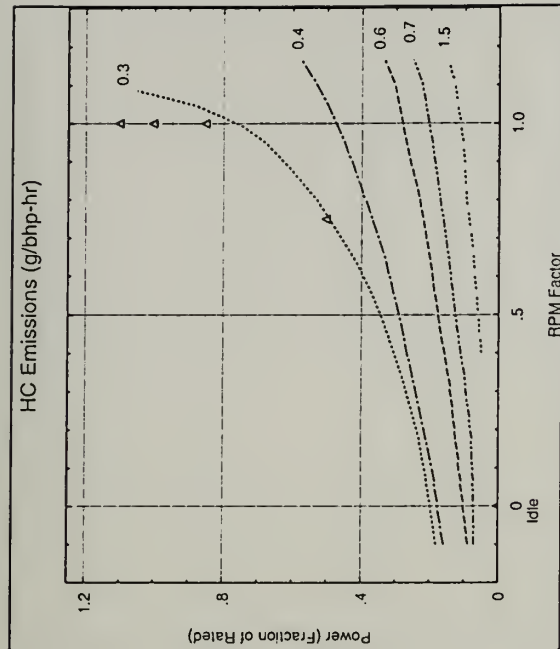
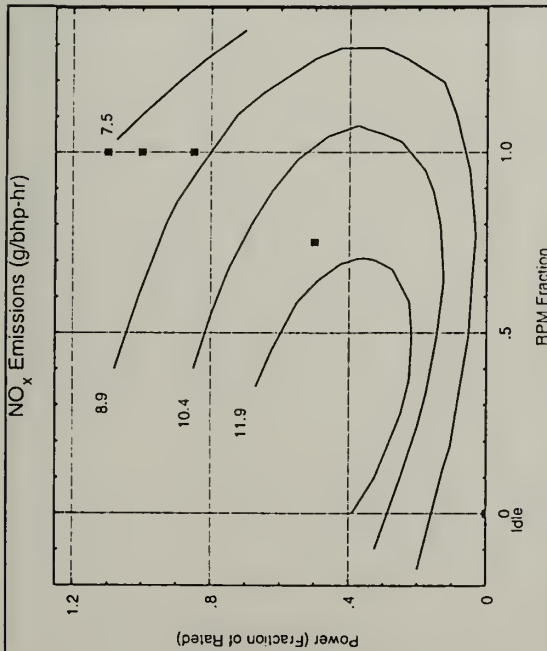


Figure C-4
U.S.N.
Endurance
Test
Emission
Contour
Plots

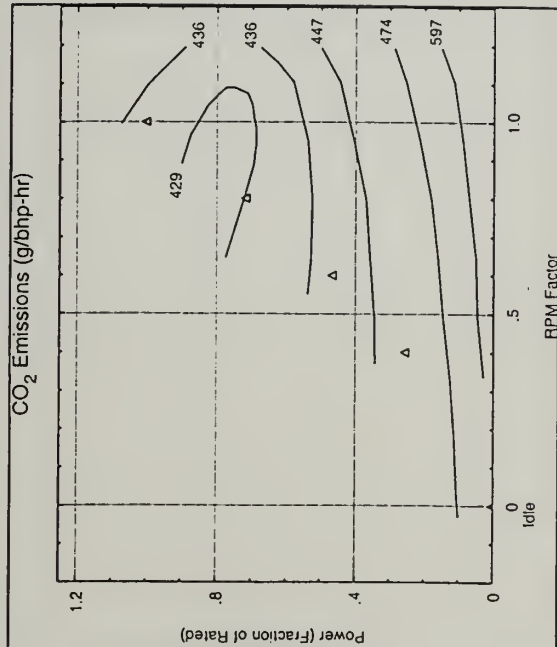
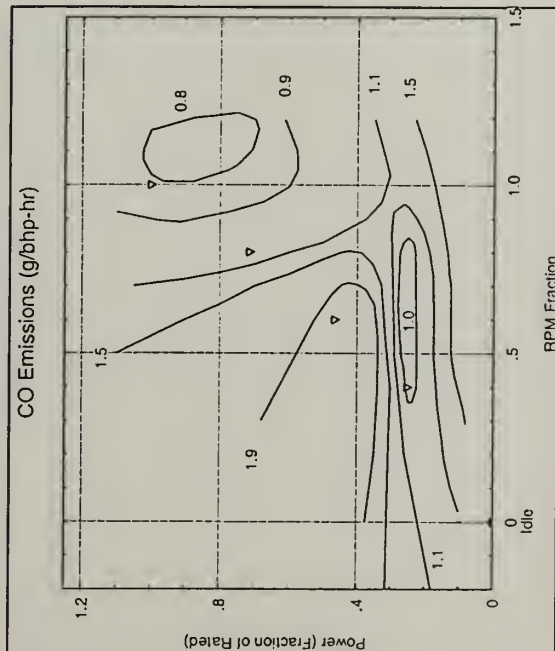
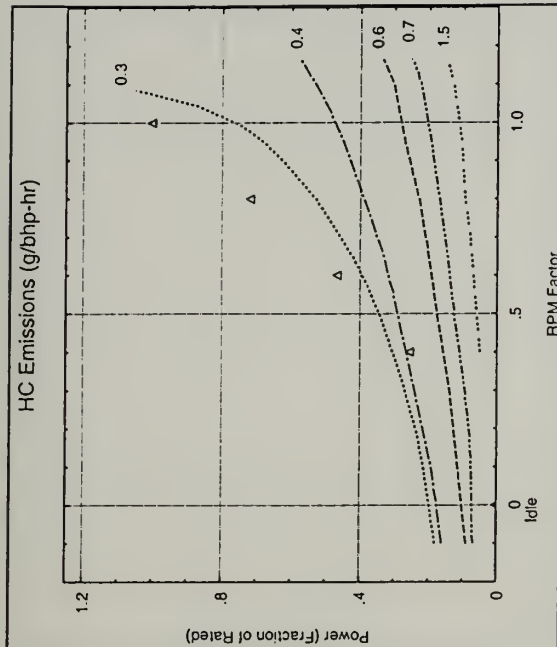
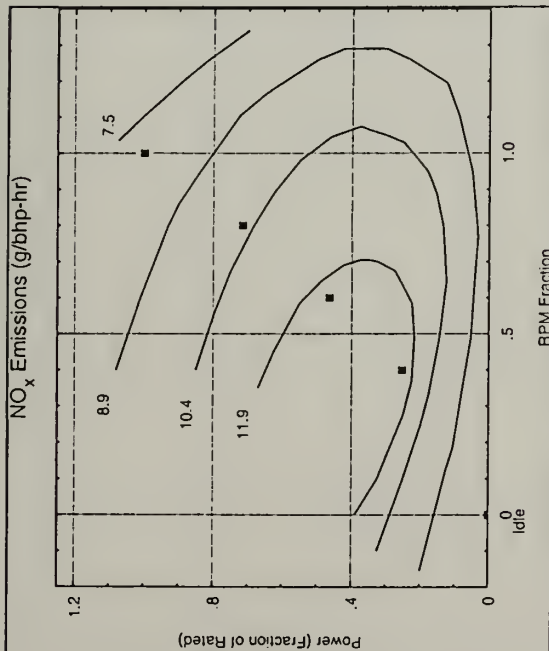


Figure C-5
 ICOMIA
 36-88
 Duty Cycle
 Emission
 Contour
 Plots

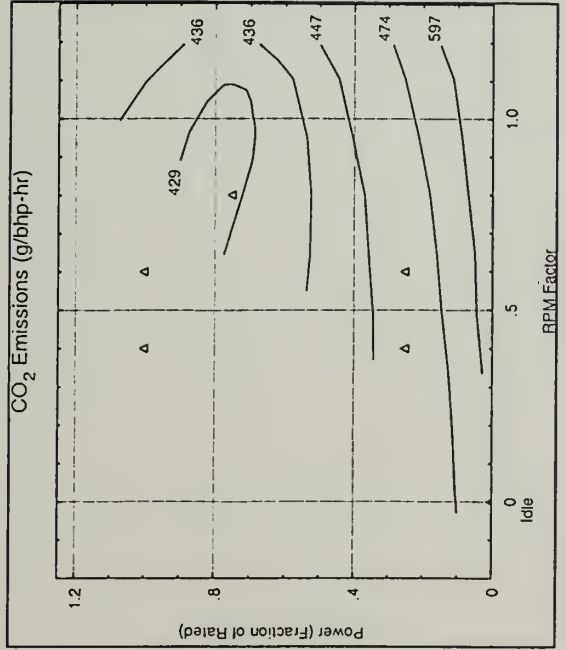
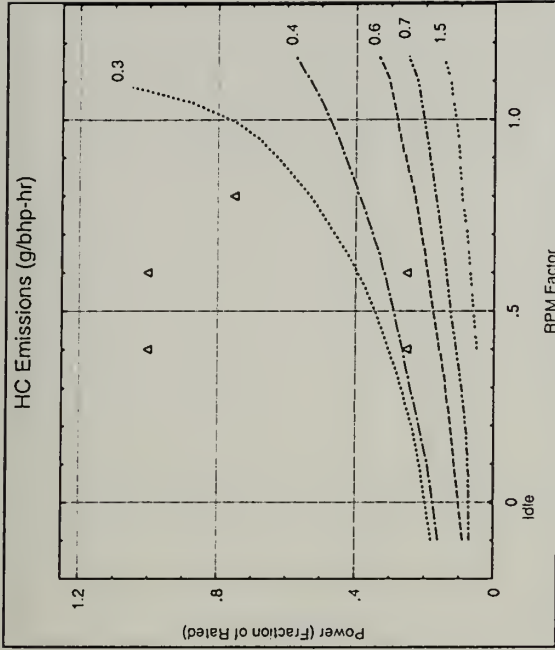
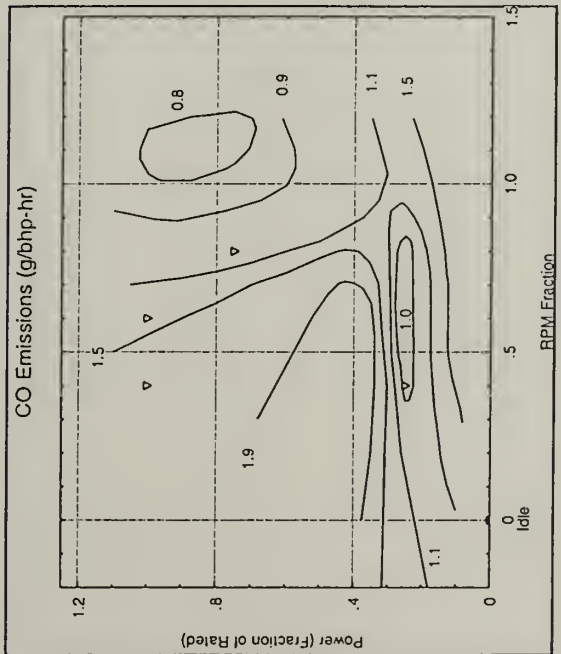
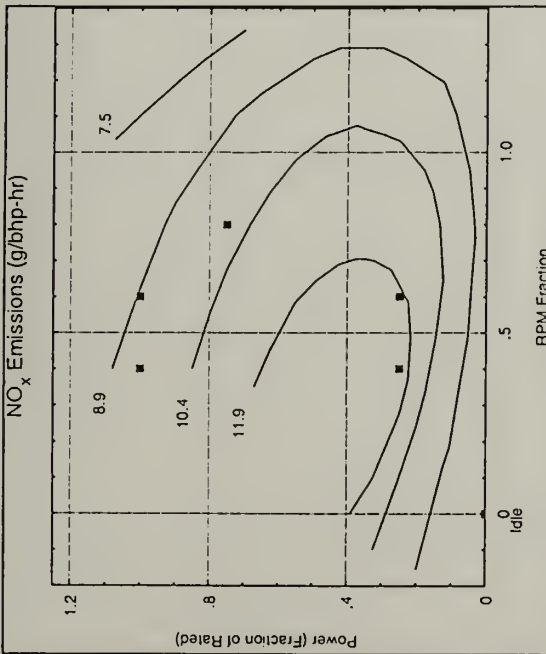


Figure C-6
Japan
Heavy-
Duty
Diesel
Duty Cycle
Emission
Contour
Plots

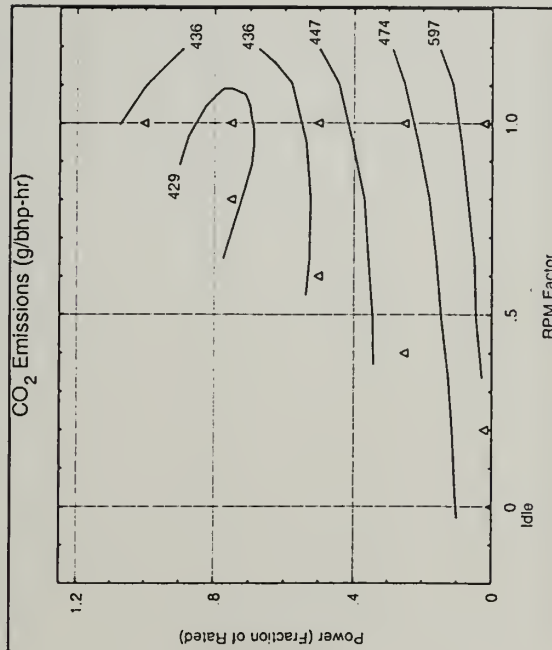
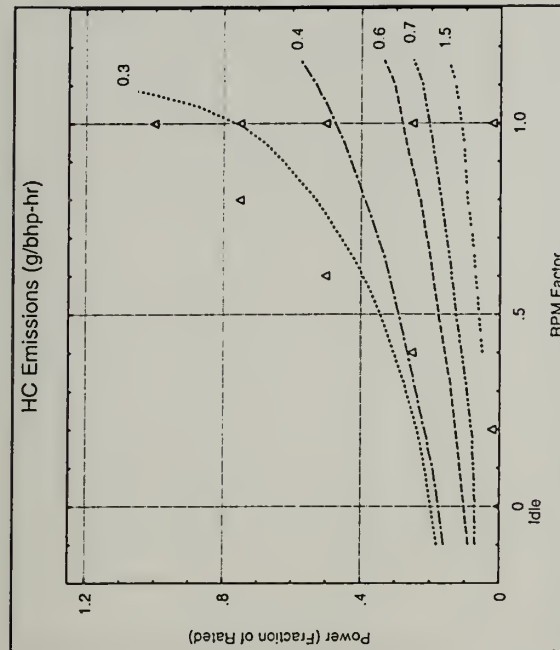
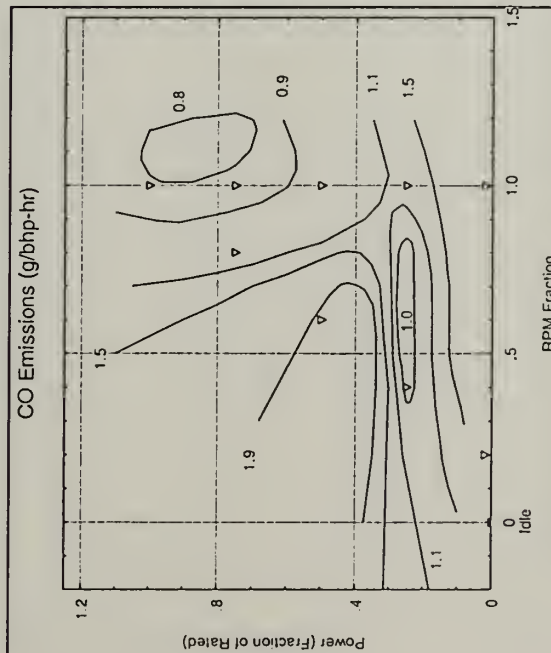
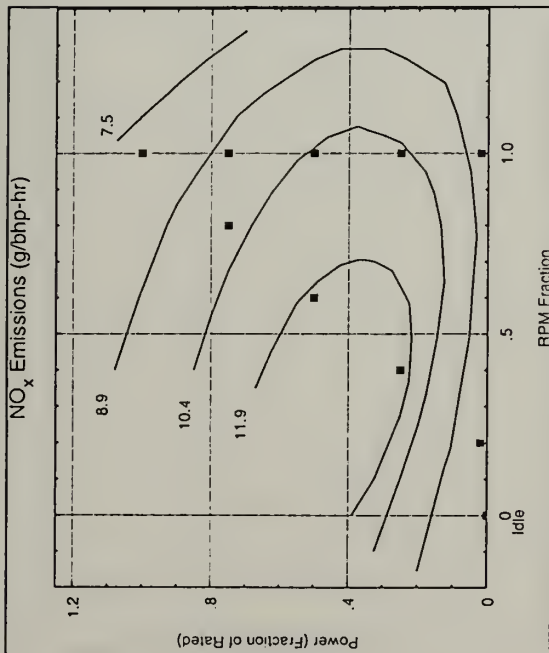


Figure C-7
US EPA
13-Mode
Duty Cycle
Emission
Contour
Plots

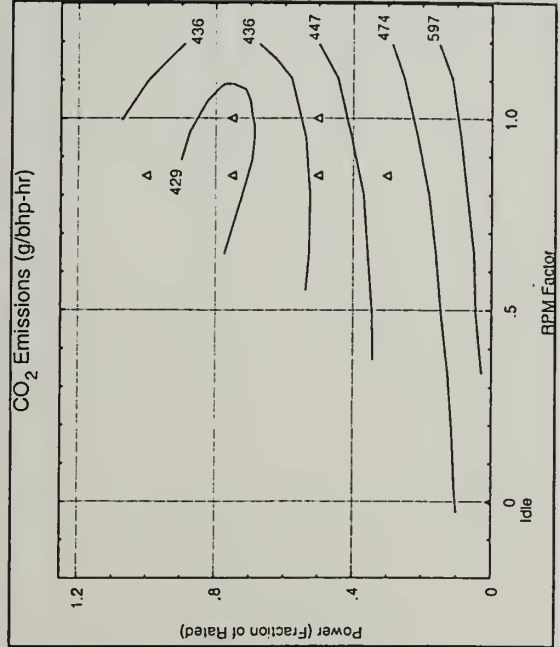
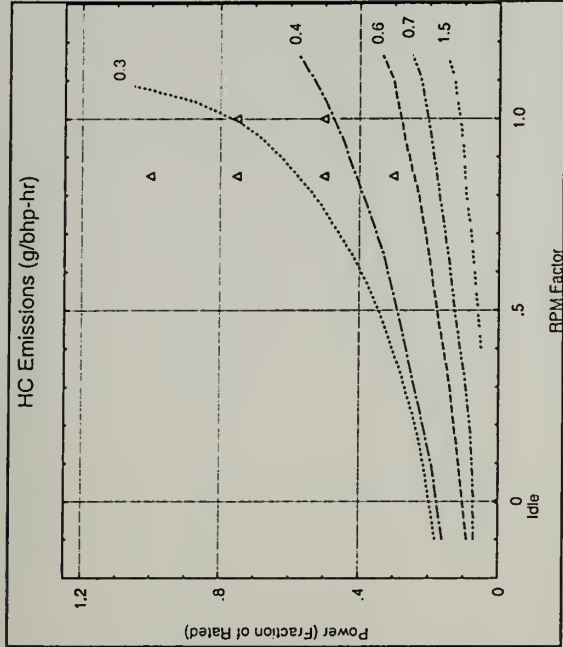
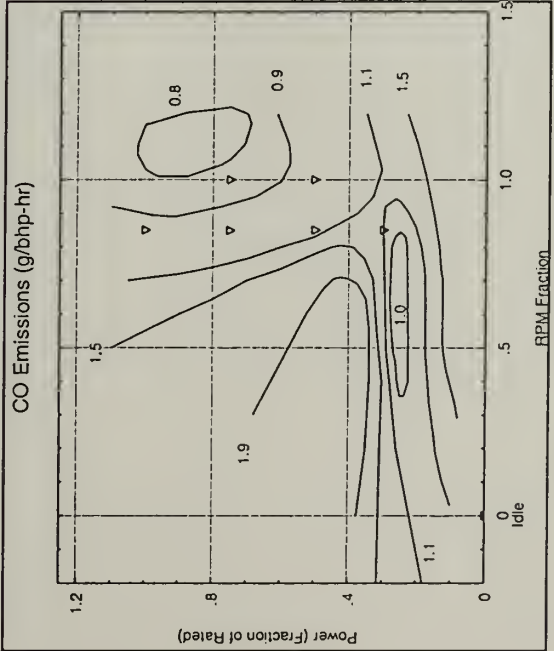
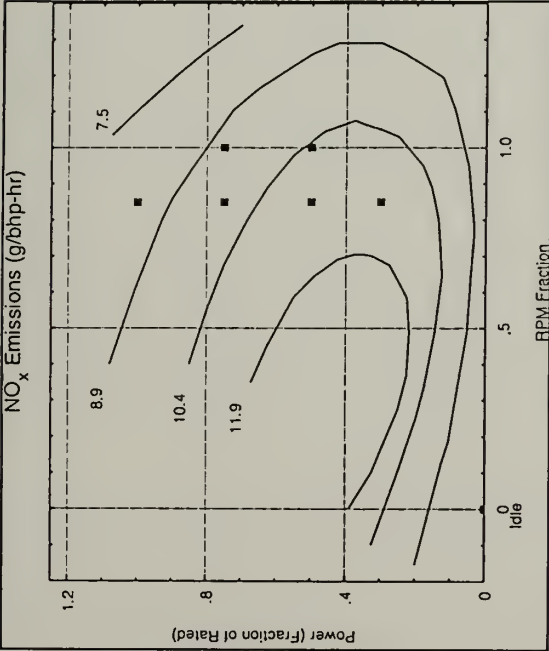


Figure C-8
CARB
8-Mode
Duty Cycle
Emission
Contour
Plots

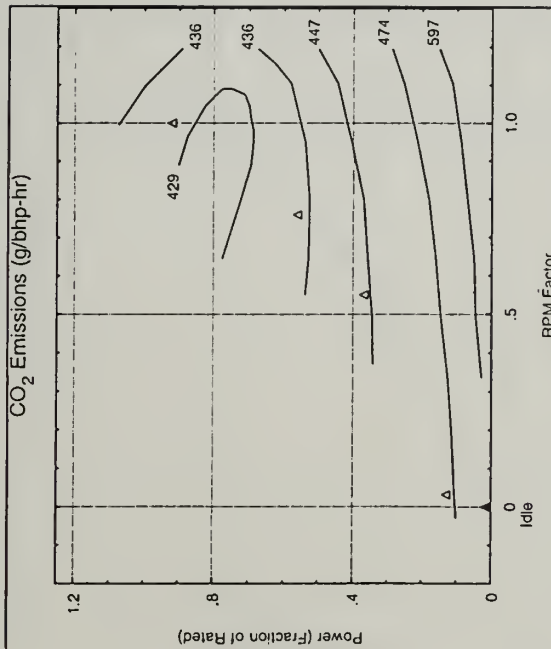
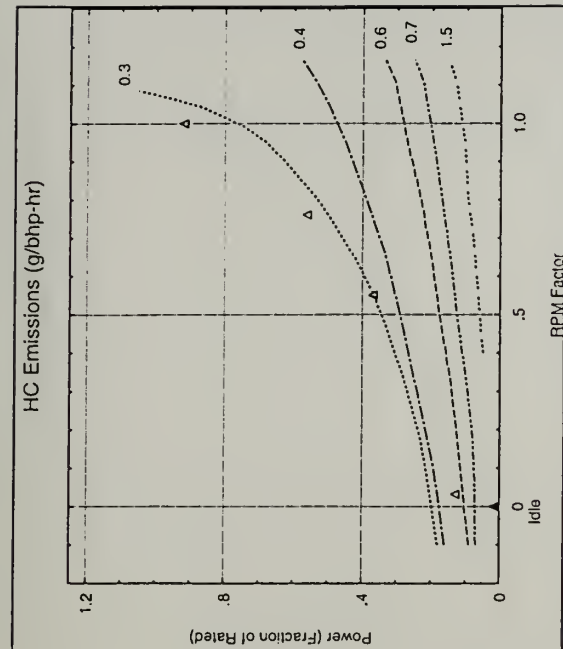
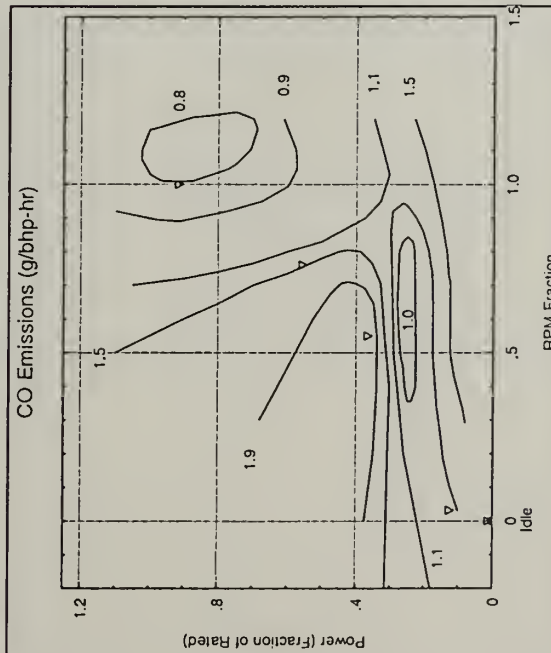
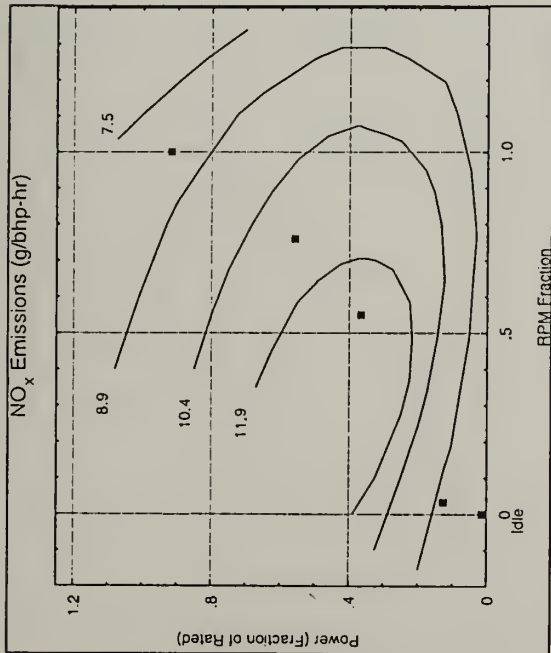


Figure C-9
TAO 187
Class
Duty Cycle
Emission
Contour
Plots

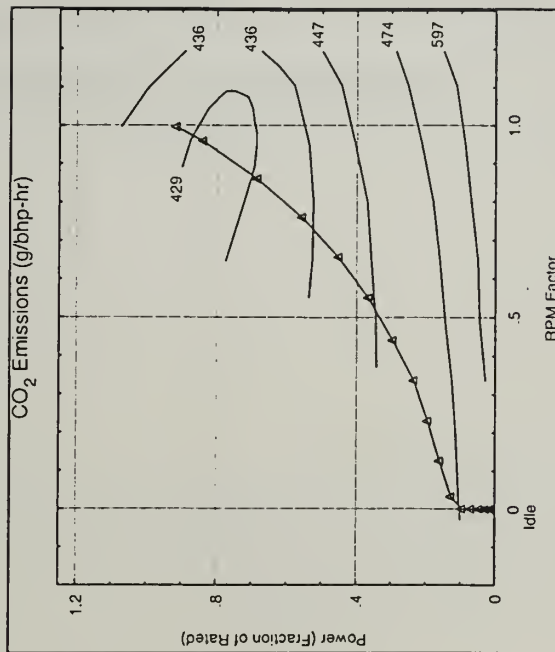
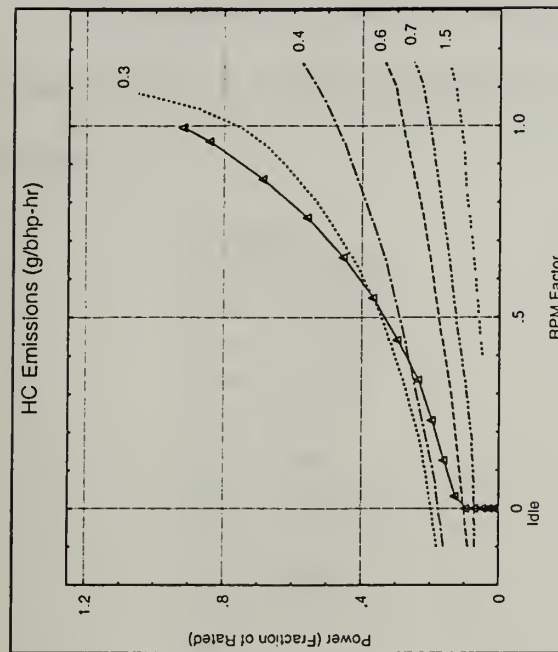
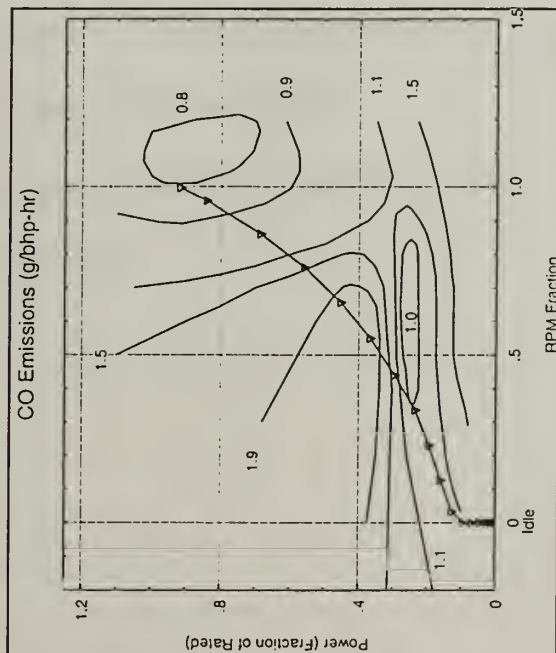
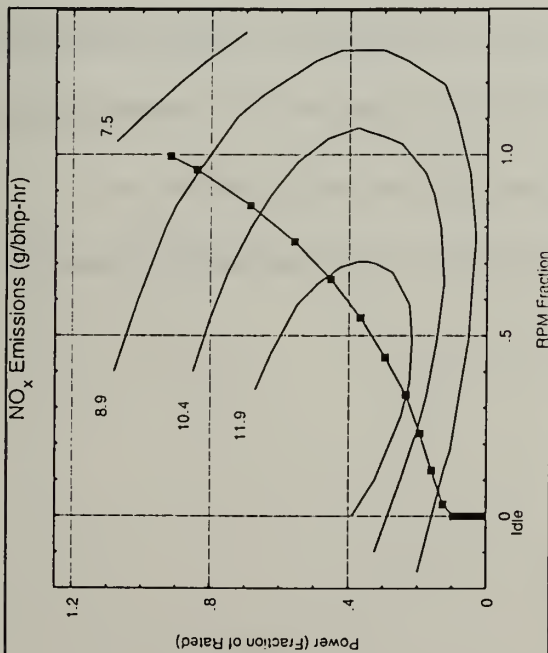


Figure C-10
TAO 187
Propeller
Curve
Emission
Contour
Plots

Appendix D: Exhaust Stack Emission *CHEMKIN* Data

This appendix contains the sample *CHEMKIN* input, and actual interpreter output file, fort.16, used in the analysis of Section 5.2. The input file is as follows:

```
1.8 688.7
CO2 5.338E-2
C2H6 1.639E-4
C4H8 1.74E-5
C3H6 4.44E-6
CH 1.33E-5
NO 1.399E-3
NO2 2.399E-4
H2O 8.77E-3
O2 1.498E-1
N2 7.862E-1
END
1.0 0.001
```

The first line specifies the inlet pressure (1.8 atmospheres) and inlet temperature (688.7° K). The next ten lines specify the species concentration at the turbocharger exit expressed as mole fraction. The last line specifies the total time of interest (1.0 seconds) and the time step (0.001 seconds).

The next two pages provide the interpreter output file, fort.16, and the third page summarizes the output from *CHEMKIN*.

CHEMKN INTERMETER OUTPUT: CHEMKN-II Version 2.3 Dec. 1990
DOUBLE PRECISIONELEMENTS
CONSIDEREDATOMIC
WEIGHT1. H 1.00797
2. O 15.9994
3. C 12.0112
4. N 14.0067

C

P

H

H

A

R

SPECIES
CONSIDERED

E S G MOLECULAR

E E WEIGHT

TEMPERATURE

LOW HIGH

ELEMENT COUNT

H O C N

1. C4H8

2. C4H6

3. C4H2

4. C4H

5. C3H6

6. C3H4

7. C3H2

8. C2H6

9. C2H5

10. C2H4

11. C2H3

12. C2H2

13. C2H

14. CH4

15. CH3

16. CH2

17. CH

18. CH2O

19. CH3O

20. CH2O

21. HCO

22. CO2

23. CO

24. CH3HCO

25. CH3CO

26. CH2CO

27. H2

28. H

29. O2

30. O

31. OH

32. HO2

33. H2O2

34. H2O

35. N2

36. NO

37. NO2

38. N

REACTIONS CONSIDERED

1. C4H8+O=C3H6+CH2O
2. C4H8+OH=C2H5+CH3HCO
3. C4H8+O=C2H5+CH3CO
4. C3H6+O=CH2O+C2H4
5. C3H6+O=CH3+CH3CO
6. C3H6+O=C2H5+HCO
7. C3H6+OH=CH3+CH3HCO
8. C3H6+OH=C2H5+CH2O
9. C3H4+O=CH2O+C2H2
10. C3H4+OH=CH2O+C2H3
11. C3H4+O=HCO+C2H3
12. C3H4+OH=HCO+C2H4
13. C2H6+O2=C2H5+HO2
14. C2H6+CH3=C2H5+CH4
15. C2H6+H=C2H5+H2
16. C2H6+O=C2H5+OH
17. C2H6+OH=C2H5+H2O
18. C2H5+H=C2H4+H+M
19. C2H5+O2=C2H4+HO2
20. C2H5=C2H2O+CH3
21. C3H6=C2H3+CH3
22. C2H5+C2H3=C4H8
23. C2H3+C2H3=C4H6
24. C2H4+N=C2H2+H2+M
25. C2H4+M=C2H3+H+M
26. C2H4+C2H4=C2H3+C2H5
27. C2H3+M=C2H2+H+M
28. C2H3+O2=C2H2+HO2
29. C2H4+H=C2H3+H2
30. C2H4+OH=C2H3+H2O
31. C2H4+O=CH3+HCO
32. C2H4+O=CH2O+CH2
33. C2H4+OH=CH3+CH2O
34. C2H3+H=C2H2+H2
35. C2H3+O=CH2CO+H
36. C2H3+OH=C2H2+H2O
37. C2H3+C2H4=C4H6+H
38. C2H2+N=C2H+H+M
39. C2H2+O2=HCCO+OH
40. C2H2+O2=HCO+HCO
41. C2H2+H=C2H+H2
42. C2H2=C2H+OH
43. C2H2+O=C2H+CO
44. C2H2+O=HCCO+H
45. C2H2+OH=CH2CO+H
46. C2H2+OH=C2H+H2O
47. C2H2+OH=CH3+CO
48. C2H2+C2H=C4H2+H
49. C4H2+OH=C3H2+HCO
50. C4H2+M=C4H+H+M
51. CH2CO+M=CH2+CO+M
52. CH2CO+OH=CH2O+HCO
53. CH2CO+OH=HCCO+H2O
54. CH2CO+O=HCCO+OH
55. CH2CO+O=HCO+HCO
56. CH2CO+H=HCCO+H2
57. CH2CO+H=CH3+CO
58. HCCO+O2=CO+CO+OH
59. HCCO+O=CO+CO+H
60. HCCO+H=CH2+CO
61. HCCO+OH=HCO+H+CO
62. HCCO+CH2=C2H3+CO

A	b	E
5.01E+12	0.0	0.0
2.57E+13	0.0	0.0
5.01E+12	0.0	0.0
5.89E+13	0.0	5000.0
5.01E+12	0.0	600.0
3.55E+12	0.0	0.0
7.08E+12	0.0	0.0
7.94E+12	0.0	0.0
1.00E+12	0.0	0.0
1.00E+12	0.0	0.0
1.00E+12	0.0	0.0
1.00E+12	0.0	0.0
1.00E+12	0.0	51000.0
1.00E+13	0.0	8280.0
5.50E-01	4.0	5200.0
5.37E+02	3.5	6360.0
2.51E+13	0.0	0.0
8.71E+09	1.1	1810.0
2.00E+15	0.0	30000.0
1.00E+12	0.0	5000.0
1.00E+13	0.0	0.0
6.31E+15	0.0	85800.0
8.91E+12	0.0	0.0
8.91E+12	0.0	0.0
9.33E+16	0.0	77200.0
6.31E+18	0.0	108720.0
5.01E+14	0.0	64700.0
7.94E+14	0.0	31500.0
1.00E+12	0.0	10000.0
6.31E+07	2.0	6000.0
4.79E+12	0.0	1230.0
3.31E+12	0.0	1130.0
2.51E+13	0.0	5000.0
2.00E+12	0.0	960.0
2.00E+13	0.0	2500.0
3.31E+13	0.0	0.0
5.01E+12	0.0	0.0
1.00E+12	0.0	7300.0
4.17E+16	0.0	107000.0
5.01E+12	0.0	23500.0
3.98E+12	0.0	28000.0
2.00E+14	0.0	19000.0
3.16E+15	-0.6	15000.0
2.19E+10	1.0	2580.0
3.55E+04	2.7	1390.0
3.24E+11	0.0	200.0
6.31E+12	0.0	7000.0
1.20E+12	0.0	500.0
3.98E+13	0.0	0.0
6.46E+12	0.0	1000.0
3.47E+17	0.0	80000.0
2.00E+16	0.0	60000.0
2.82E+13	0.0	0.0
1.00E+13	0.0	0.0
1.00E+13	0.0	0.0
1.00E+13	0.0	2410.0
1.00E+13	0.0	0.0
1.00E+13	0.0	0.0
6.31E+11	0.0	3400.0
1.20E+12	0.0	2000.0
5.01E+12	0.0	0.0
2.00E+12	0.0	0.0
3.02E+13	0.0	0.0

(k = A T**D exp(-E/RT))

63.	CH4+N=CH3+H+M	2.00E+17	0.0	88000.0	127.	HCO+O=CO2+H	1.00E+13	0.0	0.0
64.	CH4+O2=CH3+HO2	7.90E+13	0.0	56000.0	128.	HCO+O2=HO2+CO	3.30E+13	-0.4	0.0
65.	CH4+H=CH3+H2	2.20E+04	3.0	8750.0	129.	HCO+O=CO+OH	1.00E+14	0.0	0.0
66.	CH4+O=CH3+OH	1.60E+06	2.4	7400.0	130.	CO+O+M=CO2+M	3.20E+13	0.0	-4200.0
67.	CH4+OH=CH3+H2O	1.60E+06	2.1	2460.0	131.	CO+OH=CO2+H	1.51E+07	1.3	-1758.0
68.	CH4+HO2=CH3+H2O2	2.00E+13	0.0	18000.0	132.	CO+O2=CO2+O	1.60E+13	0.0	41000.0
69.	CH3HCO=CH3+HCO	7.08E+15	0.0	81760.0	133.	HO2+CO=CO2+OH	5.80E+13	0.0	22934.0
70.	CH3HCO=CH3CO+H	5.01E+14	0.0	87860.0	134.	H2+O2=2OH	1.70E+13	0.0	47780.0
71.	CH3HCO+O2=CH3CO+HO2	2.00E+13	0.5	42200.0	135.	OH+H2=H2O+H	1.17E+09	1.3	3626.0
72.	CH3HCO+H=CH3CO+H2	3.98E+13	0.0	4200.0	136.	H+O2=OH+O	5.13E+16	-0.8	16507.0
73.	CH3HCO+OH=CH3CO+H2O	1.00E+13	0.0	0.0	137.	O+H2=OH+H	1.80E+10	1.0	8826.0
74.	CH3HCO+O=CH3CO+OH	5.01E+12	0.0	1790.0	138.	H+O2+M=HO2+M	3.61E+17	-0.7	0.0
75.	CH3HCO+CH3=CH3CO+CH4	1.70E+12	0.0	8430.0		Enhanced by	1.860E+01		
76.	CH3HCO+HO2=CH3CO+H2O2	1.70E+12	0.0	10700.0		Enhanced by	4.200E+00		
77.	CH3CO=CH3+CO	3.02E+13	0.0	17240.0		Enhanced by	2.860E+00		
78.	CH3+O2=CH3O+O	4.79E+13	0.0	29000.0		Enhanced by	2.110E+00		
79.	CH3+CH3=C2H6	1.00E+13	0.0	0.0		Enhanced by	1.260E+00		
80.	CH3+CH3=C2H5+H	7.94E+14	0.0	26520.0	139.	OH+HO2=H2O+O2	7.50E+12	0.0	0.0
81.	CH3+CH3=C2H4+H2	1.00E+16	0.0	32000.0	140.	H+HO2=2OH	1.40E+14	0.0	1073.0
82.	CH3+OH=CH3O+H	2.00E+16	0.0	27410.0	141.	H+HO2=H2O+O	5.01E+13	0.0	1000.0
83.	CH3+CH2O=CH4+HCO	1.00E+10	0.5	6000.0	142.	O+HO2=O2+OH	1.40E+13	0.0	1073.0
84.	CH3+HCO=CH4+CO	3.02E+11	0.5	0.0	143.	O+O+M=O2+M	1.91E+13	0.0	-1790.0
85.	CH3+HO2=CH3O+OH	2.00E+13	0.0	0.0	144.	2OH+O=H2O	6.00E+08	1.3	0.0
86.	CH3+M=CH2+H+M	2.00E+16	0.0	91600.0	145.	O+OH+M=HO2+M	1.00E+17	0.0	0.0
87.	CH3O+M=CH2O+H+M	5.01E+13	0.0	21000.0	146.	H+H+M=H2+M	1.00E+18	-1.0	0.0
88.	CH3O+O2=CH2O+HO2	1.00E+12	0.0	6000.0	147.	H+H+H2=H2+H2	9.20E+16	-0.6	0.0
89.	CH3O+H=CH2O+H2	2.00E+13	0.0	0.0	148.	H+H+H2O=H2+H2O	6.00E+19	-1.3	0.0
90.	CH3+O=CH2O+H	6.80E+13	0.0	0.0	149.	H+H+CO2=H2+CO2	5.49E+20	-2.0	0.0
91.	CH3+OH=CH2O+H2	1.00E+12	0.0	0.0	150.	H+OH+M=H2O+M	1.60E+22	-2.0	0.0
92.	CH3+H=CH2+H2	9.00E+13	0.0	5000.0		Enhanced by	5.000E+00		
93.	CH3+H=CH2+H2	1.50E+13	0.0	15100.0		Enhanced by	5.000E+00		
94.	CH2+OH=CH2O+H	2.50E+13	0.0	0.0	151.	H+O+M=OH+M	6.20E+16	-0.6	0.0
95.	CH2+O=CH+H2O	4.50E+13	0.0	3000.0		Enhanced by	1.25E+13		
96.	CH2+O=CH+OH	2.00E+11	0.7	25000.0	152.	H+HO2=H2+O2	2.00E+12	0.0	0.0
97.	CH2+H=CH+H2	2.50E+11	0.7	25700.0	153.	HO2+HO2=H2O2+O2	1.30E+17	0.0	45500.0
98.	CH2+CH2=C2H3+H	5.01E+12	0.0	0.0	154.	H2O2+N=OH+OH+M	1.60E+12	0.0	3800.0
99.	CH2+CH2=C2H2+H2	3.16E+13	0.0	0.0	155.	H2O2+H=HO2+H2	1.00E+13	0.0	1800.0
100.	CH2+C2H3=CH3+C2H2	3.02E+13	0.0	0.0	156.	H2O2+OH=H2O+HO2	1.40E+14	0.0	75800.0
101.	C2H+O2=HCO+O+O	3.31E+12	0.0	0.0	157.	O+N2=NO+N	6.40E+09	1.0	6280.0
102.	C2H+O2=HCO+CO	1.00E+13	0.0	7000.0	158.	N+O2=NO+O	4.00E+13	0.0	0.0
103.	C2H+O=CO+CH	5.01E+13	0.0	0.0	159.	OH+N=NO+H	2.20E+09	0.0	-1100.0
104.	C2H+C2H3=C2H2+C2H2	3.02E+13	0.0	0.0	160.	2NO+O2=2NO2	2.10E+12	0.0	-476.9
105.	CH+O2=HCO+O	3.30E+13	0.0	0.0	161.	NO+HO2=NO2+OH	1.50E+15	0.0	-1867.8
106.	CH+O=CO+H	5.70E+13	0.0	0.0	162.	NO+O+M=NO2+M	1.00E+13	0.0	596.1
107.	CH+OH=HCO+H	3.00E+13	0.0	0.0	163.	NO2+O=NO+O2	3.50E+14	0.0	1470.4
108.	CH+O2=CO+OH	1.35E+11	0.7	25700.0	164.	NO2+H=NO+OH			
109.	CH+CO2=HCO+CO	3.40E+12	0.0	690.0		NOTE: A units mole-cm-sec-K, E units cal/mole			
110.	CH2+CO2=CH2O+CO	1.10E+11	0.0	1000.0					
111.	CH2+O=CO+H+H	3.00E+13	0.0	0.0					
112.	CH2+O=CO+H2	5.00E+13	0.0	0.0					
113.	CH2+O2=CO2+H+H	1.60E+12	0.0	1000.0					
114.	CH2+O2=CH2O+O	5.00E+13	0.0	9000.0					
115.	CH2+O2=CO2+H2	6.90E+11	0.0	500.0					
116.	CH2+O2=CO+H2O	1.90E+10	0.0	-1000.0					
117.	CH2+O2=CO+OH+H	8.60E+10	0.0	-500.0					
118.	CH2+O2=HCO+OH	4.30E+10	0.0	-500.0					
119.	CH2O+OH=HCO+H2O	3.43E+09	1.2	-447.0					
120.	CH2O+H=HCO+H2	2.19E+08	1.8	3000.0					
121.	CH2O+N=HCO+H+M	3.31E+16	0.0	81000.0					
122.	CH2O+O=HCO+OH	1.81E+13	0.0	3082.0					
123.	CH2O+HO2=HCO+H2O2	1.00E+12	0.0	8000.0					
124.	HCO+OH=CO+H2O	5.00E+12	0.0	0.0					
125.	HCO+N=H+CO+M	1.60E+14	0.0	14700.0					
126.	HCO+H=CO+H2	4.00E+13	0.0	0.0					

NO ERRORS FOUND ON INPUT...CHEMKIN LINKING FILE WRITTEN.

WORKING SPACE REQUIREMENTS ARE

INTEGER: 2815

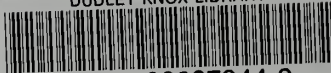
REAL: 2201

CHARACTER: 42

MOLES FRACTION/SECOND		C4H6	C4H2	C4H	C3H6	C3H4	C3H2	C2H6	C2H5	C2H4	C2H3	C2H2	C2H	CH4	CH3	CH2
SPECIES:	C4H8	54.092	50.061	49.053	42.081	40.065	38.049	30.07	29.062	28.054	27.046	26.038	25.03	16.043	15.035	14.027
MW:	56.108															
TIME																
0	0.000017	0	0	0	4.4E-06	0	0	0.000025	0	0	0	0	0	0	0	0
0.001	2.4E-06	2.2E-11	5.8E-18	1.6E-33	2.7E-06	2.1E-16	3.0E-19	0.000024	3.1E-09	0.000018	4.0E-10	1.8E-08	3.7E-17	1.6E-07	1.8E-06	2.1E-13
0.002	2.4E-06	2.2E-11	6.0E-18	4.4E-33	2.7E-06	2.2E-16	3.1E-19	0.000024	1.9E-10	0.000018	5.1E-11	1.8E-08	2.4E-18	2.0E-07	8.4E-07	6.2E-15
0.003	2.4E-06	2.2E-11	6.0E-18	7.2E-33	2.7E-06	2.2E-16	3.1E-19	0.000024	9.9E-11	0.000018	4.1E-11	1.8E-08	1.2E-18	2.2E-07	5.5E-07	2.1E-15
0.01	2.4E-06	2.3E-11	6.1E-18	2.7E-32	2.7E-06	2.3E-16	3.2E-19	0.000025	2.3E-11	0.000018	3.0E-11	1.9E-08	3.0E-19	2.6E-07	1.5E-07	1.5E-16
0.02	2.3E-06	2.4E-11	6.2E-18	5.6E-32	2.6E-06	2.5E-16	3.2E-19	0.000025	1.0E-11	0.000018	2.5E-11	2.0E-08	1.4E-19	2.9E-07	7.4E-08	3.8E-17
0.1	2.3E-06	2.8E-11	6.3E-18	2.9E-31	2.6E-06	3.4E-16	3.3E-19	0.000025	2.0E-12	0.000018	1.3E-11	2.2E-08	3.2E-20	3.3E-07	1.4E-08	3.4E-17
0.92	2.3E-06	4.7E-11	6.8E-18	2.8E-30	2.6E-06	8.1E-16	3.4E-19	0.000025	9.5E-13	0.000018	7.2E-12	2.7E-08	1.8E-20	4.2E-07	7.6E-09	1.9E-18
TIME	CH	HCO	CH3O	CH2O	HCO	CH3HCO	CH3CO	CH2CO	TOTAL HC	CO2	CO	O2	N2	NO	NO2	H2O
MW	13.019	41.03	31.03	30.026	29.019	44.054	43.046	42.037		44.01	28.011	31.999	28.013	30.006	46.006	18.015
0	0.000013	0	0	0	0	0	0	0	0.00006	0.05338	0.000164	0.1498	0.7862	0.001399	0.00024	0.00877
0.001	1.8E-20	2.3E-13	1.1E-10	2.7E-06	6.8E-12	1.0E-05	5.6E-12	5.3E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0.002	3.3E-23	3.3E-14	6.2E-12	2.7E-06	4.4E-13	1.0E-05	1.6E-12	5.2E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0.003	5.9E-24	2.9E-14	2.8E-12	2.7E-06	2.3E-13	1.0E-05	9.9E-13	5.2E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0.01	9.7E-26	2.4E-14	4.7E-13	2.7E-06	5.4E-14	1.0E-05	2.8E-13	5.1E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0.02	1.1E-26	2.4E-14	2.0E-13	2.7E-06	2.5E-14	1.0E-05	1.3E-13	5.1E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0.1	1.9E-28	2.7E-14	3.5E-14	2.7E-06	5.0E-15	9.9E-06	2.5E-14	5.0E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000266	0.00878
0.92	5.2E-29	3.2E-14	1.9E-14	2.7E-06	2.5E-15	9.9E-06	1.4E-14	4.9E-09	0.000061	0.0534	0.000184	0.15	0.786	0.00137	0.000269	0.00878
GRAMS/SECOND																
TIME	DISTANCE	HC	CO2	CO	O2	N2	NO	NO2	H2O							
0	0	0.472107	528.8875	1.033572	1079.149	4958.223	9.450596	2.484724	35.56864							
0.001	0.13404	0.453638	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919							
0.002	0.26808	0.453225	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919							
0.003	0.40212	0.453593	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919							
0.01	1.3404	0.453437	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919							
0.02	2.6808	0.453102	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919							
0.1	13.869	0.452718	529.0857	1.160325	1080.59	4956.961	9.254694	2.75505	35.60919							
0.92	127.5948	0.452527	529.0857	1.160325	1080.59	4956.961	9.254694	2.786122	35.60919							

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